The Effect of Glaucoma on Gaze Behaviour and Mobility While Walking in Cluttered Environments

by

Andreas B. Miller

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Name:	**Andreas B. Miller**
Degree:	**Master of Science (BPK)**
Title:	***The Effect of Glaucoma on Gaze Behaviour and Mobility While Walking in Cluttered Environments.***
Examining Committee:	**Chair:** Dr. Tom Claydon Associate Professor

Dr. Dan Marigold
Senior Supervisor
Associate Professor

Dr. Robert Strath
Supervisor
Adjunct Professor

Dr. Miriam Spering
External Examiner
Professor
Ophthalmology & Visual Sciences
University of British Columbia

Date Defended/Approved: August 14, 2015

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Abstract

Glaucoma causes loss of peripheral vision and is a leading cause of blindness worldwide. It primarily affects older adults, limiting their mobility and increasing their risk for falls. This thesis investigated the effects of visual field loss from glaucoma on gaze behaviour and mobility during two visually demanding walking tasks while multitasking; stepping to targets, and navigating around obstacles. Older adults with glaucoma had less precise foot placement, looked to the same target more often, and looked toward future targets sooner, compared to healthy older adults. Subjects with glaucoma also collided with obstacles more frequently, looked to obstacles more often, and looked more frequently toward their feet. Dual tasking also disrupted mobility and gaze during the walking tasks. For this population these findings provide the framework to design future walking and gaze training programs for people with glaucoma to improve their quality of life.

Keywords: glaucoma; visual impairment; mobility; dual tasking; gaze

Dedication

For Megan and Joshua.

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List of Acronyms

AOI	Area of interest
AMD	Age-related macular degeneration
AP	Anterior-posterior
FEF	Frontal eye field
GON	Glaucomatous optic neuropathy
GR	Ground segment
IOP	Intraocular pressure
LIP	Lateral intraparietal area
MD	Mean deviation
ML	Medial-lateral
MMSE	Mini-mental state exam
MST	Medial superior temporal
MT	Middle temporal
OCT	Optical coherence tomography
OU	Oculus uterque (both eyes)
PD	Parkinson’s disease
PPRF	Paramedian pontine reticular formation
RP	Retinitis pigmentosa
SEF	Supplementary eye field
SC	Superior colliculus
TUG	Timed up-and-go
UFOV	Useful field of view
VOR	Vestibulo-ocular reflex

Chapter 1. Introduction and Background Literature

Glaucoma is an eye disease that causes progressive vision loss in tens of millions of people worldwide (Quigley & Broman, 2006). Despite the best efforts of the research community it has not been cured, and is treated with varying levels of success. Since much of the research on glaucoma is directed on preserving visual function and developing better treatments, there is a large gap in knowledge related to helping people manage their vision loss and improving their quality of life. Important everyday tasks like reading, driving, and walking can feel out of reach or unsafe for those with advanced glaucoma. We must deal with many distractions while driving and walking, thus further complicating these tasks. In fact, distractions lead to mobility deficits in older adults at the typical age for glaucoma (Hegeman et al., 2012; Hirashima et al., 2015). Population-level surveys regarding the loss of mobility and increased risk for injury due to vision loss from glaucoma are well-documented in the literature (Black et al., 2011; Tanabe et al., 2012), yet it is unknown how this vision loss specifically affects mobility. It is also not clear how people with glaucoma direct their gaze while walking, and how this in turn affects mobility performance. This thesis focuses on elucidating the interaction between gaze behavior and mobility during walking in people with glaucoma, and the impact of multitasking has on this interaction.

Chapter one comprises a literature review starting with an introduction into the pathophysiology and treatments for glaucoma, followed by an explanation of the crucial role vision plays during walking and the gaze behaviors that allow us to move effectively within our environment. A description of the interaction between gaze behavior and mobility performance during natural aging will then set the scene for a report on the research investigating gaze behavior and mobility with various levels of vision loss. Finally, how these aspects can be affected by simultaneously performing a secondary task (dual tasking) will be discussed. Chapter two outlines the first experiment that was conducted where people with glaucoma participated in a precision walking task that involved stepping on targets, including conditions requiring dual tasking. In chapter three, the second experiment where subjects must navigate around obstacles, with and without dual tasking, is detailed. Lastly, chapter four comprises a full discussion of the findings of this thesis and the implications it has for the future development of gaze-mobility training to improve the lives of people with glaucoma.

1.1. The Aging Visual System

Vision is integral for walking, as it allows us to navigate various terrain in a predictive manner, and guides foot placement as we step. Information from our surroundings is obtained through the eye and processed in an array of subcortical and cortical brain regions that make up the complex visual system. Light from the environment first enters the eye and is focused by the lens, on to the retina where photoreceptors that detect light are situated (Kandel et al., 2000). Visual information is then carried to the primary visual cortex and follows one of several neural streams through the occipital lobe where various features of the environment are collated to produce the image that we see (Kandel et al., 2000). As part of the aging process, many of the body's systems experience a decrease in function; the visual system is no exception. As we age the images we perceive become less clear due to many factors including decreased pupil diameter, increased scatter of light at the cornea and lens, and increased light absorption by the fluids within the eyeball. Taken together, this decreased illuminance and increased light scatter on the retina and reduces the ability to discern contrasting features of the environment (Werner et al., 1989; Glasser & Campbell, 1998). Thickening and hardening of the lens also reduces its ability to focus light (Werner et al., 1989). In addition, changes to the neural circuitry are widespread, including loss of photoreceptors, neurons, and neurotransmitters that are essential for processing vision (Spear., 1993; Jackson et al., 1999). As a result, visual acuity, visual field, contrast sensitivity, motion perception, contour integration, shape perception, and visual processing speed all decrease with age (Elliott et al., 1995; Ball & Sekuler, 1986; Roudaia et al., 2008; McKendrick et al., 2010; Kline & Birren, 1975).

Aging is associated with increased susceptibility to eye diseases including age-related macular degeneration (AMD), cataracts, diabetic retinopathy, and glaucoma

(National Coalition for Vision Health, 2010). The prevalence of these diseases increases with the ever-growing number of people over the age of 60 years, a number that is expected to increase three-fold from 737 million worldwide in 2009 to nearly two billion by 2050 (United Nations, 2010). This research aims to investigate the basis for the glaucoma-related problems that are common during visually guided walking, in the hopes of improving the quality of life of these individuals.

1.2. Glaucoma

Glaucoma affects more than 70 million people worldwide, and is the leading cause of irreversible blindness, where 10% of those with the disease are bilaterally blind (Quigley & Broman, 2006). Though its pathogenesis is understood to a certain extent, its effects remain a major concern even in the developed world. Glaucoma is often asymptomatic until severe vision loss has occurred, so treatment can come too late. The treatment options that are available only aim to slow or halt the progression of the condition rather than cure it (Leite et al., 2011; Rotchford et al., 2003).

1.2.1. Pathophysiology

There are two distinct but broad types of glaucoma: open-angle glaucoma and angle-closure glaucoma. Open-angle glaucoma is much more prevalent, making up more than 80% of the cases in the United States, and often progresses more slowly (Friedman et al., 2004). Although the end result of each type is similar, the mechanisms, rate of progression, and treatments differ and will therefore be discussed separately.

The most common cause of open-angle glaucoma is mechanical stress on the retinal ganglion cells from elevated intraocular pressure (IOP). The aqueous humor contained within the anterior chamber of the eye maintains its shape, acts a refractive index for light passing through, provides nutrition for the avascular ocular tissues of the eye, and helps with the immune response (Murthy et al., 2015). The aqueous humor has a delicate balance of secretion and absorption to control the fluid pressure in the eye to maintain homeostasis. Aqueous humor is secreted by the ciliary body located where the internal peripheral cornea contacts the sclera, and is drained through two independent pathways in that area called the trabecular meshwork and uveoscleral outflow pathways. In open-angle glaucoma, drainage is restricted at the trabecular meshwork. The increased pressure that results causes mechanical stress on the posterior structures of the eye, most notably the lamina cribrosa where the central artery, vein, and retinal ganglion cells that comprise the optic nerve exit the eye (Weinreb et al., 2014). This area is the weakest point in the wall of the eye and increased IOP can result in compression, deformation, and remodeling that cause damage to the axons of retinal ganglion cells (Burgoyne et al., 2005; Fechtner & Weinreb, 1994). As a result, both orthograde and retrograde delivery of essential trophic factors to retinal ganglion cells may be blocked, causing problematic collections of vesicles, disorganized microtubules and neurofilaments, as well as mitochondrial dysfunction (Quigley et al., 2000). The blockage of nutrients and decrease in energy production also leads to dysfunction and death of retinal ganglion cells and astrocytes, collectively known as glaucomatous optic neuropathy (GON) (Ju et al., 2008; Quigley et al., 1981). GON can also occur in people with normal IOP (normotension glaucoma) who may have abnormally low cerebrospinal fluid pressure in the optic nerve space, causing a large pressure gradient across the lamina (Ren et al., 2010; Wang et al., 2012). Other conditions that can lead to glaucoma include impaired microcirculation, altered immunity, excitotoxicity, and oxidative stress (Weinreb et al., 2014). Genetics may also factor in one's susceptibility to glaucoma. Known mutations on several genes including myocilin, optineurin, and WD repeat domain 36 are associated with a monogenic, autosomal dominant trait of glaucoma (Monemi et al., 2005; Rezai et al., 2002; Stone et al., 1997). In the case of myocilin mutations (occurring in 3% to 5% of the population), up to 90% of carriers eventually develop glaucoma (Kwon et al., 2009). Although results are encouraging for identifying susceptibility genes, they have only moderate statistical power to explain overall glaucoma risk (Weinreb et al., 2014).

The differentiation between open- and closed-angle glaucoma is that in the latter, aqueous drainage is obstructed by the iris when it creates an anatomically closed angle between the iris and the cornea, with at least 270^{o} of the angle occluded. Both types of glaucoma are generally asymptomatic for long periods of time, but closed-angle is more frequently acute. For instance, people with closed-angle glaucoma may present with rapid increases in IOP (above 30 mmHg) causing ocular pain, nausea, vomiting, intermittent blurring of vision, and haloes around lights in the affected eye(s). Closed-angle glaucoma is mainly a disorder involving the iris anatomy. When the aqueous humor experiences resistance to flow from the posterior to anterior chambers due to pupillary block, it accumulates behind the iris folding it toward the cornea, leading to a closed angle. Other factors including a plateaued shape to the iris and increases in iris volume with pupil dilation may also cause closed-angle glaucoma in susceptible eyes (Weinreb et al., 2014).

1.2.2. Clinical Features and Diagnosis

Glaucoma can be difficult to identify for the clinician since although elevated IOP is a risk-factor, its level may be lower than the 22 mmHg cut-off in 25% to 50% of cases (Weinreb & Khaw, 2004). Moreover, high IOP does not guarantee that a person will eventually develop glaucoma. Unfortunately, damage can happen for many years before visual symptoms appear, at which point significant optic nerve damage has already occurred. The three main features an ophthalmologist looks for to diagnose glaucoma is the IOP level, appearance of the optic nerve, and visual field profile. IOPs above the normal range of 12-22 mmHg are considered high, and some clinicians will treat for glaucoma on the basis of consistent high pressures alone. When IOP is causing mechanical stress in the eye, a change in the appearance of the optic nerve head and retinal nerve fiber layer can confirm the presence of glaucoma (Weinreb & Khaw, 2004). These changes are identified by ophthalmoscopic examination of the optic nerve head. Here, the clinician looks for a signature “cupping” appearance where the death of optic nerve fibers lead to a greater size of the center of the optic disk, or cup, relative to the size of the entire disk. A cup to disc ratio greater than six-tenths is generally considered indicative of glaucoma, although there is large disagreement in grading among glaucoma specialists (Jampel et al., 2009). More recently, laser scanning imaging techniques like confocal scanning laser ophthalmoscopy, scanning laser polarimetry, and most notably optical coherence tomography (OCT), enhance early identification of glaucoma and improve tracking of optic nerve fiber loss over time (Weinreb et al., 2014). OCT has become a prominent tool for diagnosing glaucoma in the last two decades by creating cross-sectional images of retinal and optic nerve tissues using depth-resolved reflection of near-infrared light to micrometer resolution (Kim et al., 2015). The third piece of evidence a clinician can use toward a diagnosis of glaucoma is perimetry, or visual field testing. These tests are done on a visual field analyzer where the subject responds when detecting an image in their periphery. Any loss of vision in the periphery above age-adjusted values and progression thereof may be interpreted as evidence of glaucoma. Due to lower blood and nutrient supply to the peripheral retina, loss of vision usually begins in the midperiphery and may progress towards central vision until only it or an island of peripheral vision remains (Weinreb et al., 2014).

1.2.3. Treatment

Since retinal ganglion cell death cannot be reversed, the main goals of treatment are ideally to stop disease progression and preserve quality of life. The only proven method to treat glaucoma is to reduce intraocular pressure (Boland et al., 2013). Results from multiple longitudinal studies show those with ocular hypertension that were not treated were more than twice as likely (9.5% vs. 4.4%) to develop signs of glaucoma five years later (Kass et al., 2002). Similarly, another study reported that glaucoma patients who received treatment for ocular hypertension showed less disease progression compared to untreated patients (Heijl et al., 2002). Lowering IOP is ideally achieved using the fewest medications with the smallest side effects. These medications are administered usually as nightly eye drops or oral tablets with various actions including reducing aqueous humor production, increasing aqueous humor outflow, or a combination of both (Weinreb et al., 2014). The new targeted intraocular pressure is based on a number of factors specific to the individual case, but is commonly in the range of a 20% to 50% reduction from glaucomatous levels (American Academy of Opthalmology, 2010). When medication is unsuccessful or side effects prevent adherence (eye irritation, headaches, respiratory problems, nausea, and/or renal stones), laser or incisional surgeries are the only option.

Laser trabeculoplasty causes biological changes in the trabecular meshwork to increase aqueous outflow and lower IOP. It is a relatively safe, quick, and effective procedure for drastically reducing IOP, but the effects decrease over time, failing 10% per year (Weinreb, et al., 2014). Trabeculectomy is the incisional surgical option used to reduce IOP, which works by removing a small part of the trabecular meshwork or adjacent corneoscleral tissue to create a drainage pathway for aqueous humor (Weinreb, et al., 2014). Alternatively, devices that drain aqueous fluid into an external reservoir are also effective, but like trabeculectomy, carry a risk of scarring and infection. Surgeries with lower risk and lower success rates are also sometimes made available, but are only a temporary solution for slowing the progression of glaucoma and cannot be repeated indefinitely.

Despite the best efforts of clinicians to diagnose and treat glaucoma in a timely manner, many patients experience significant progressive vision loss. This can occur in any area of the visual field, negatively affecting everyday life activities requiring any amount of visual attention, such as walking in a cluttered environment.

1.3. General visual control of walking

1.3.1. Central versus peripheral vision

The visual field (the entire area that can be seen when the eye is directed forward) is separated into two distinct areas, central vision and peripheral vision, both of which are important during visually guided walking. Central vision (central 5^o of the visual field) is the part vision where light is detected close to the area on the retina richest in cone photoreceptors that detect colour, called the fovea (Millodot, 2014). At the fovea there are only cones and images formed in this area have the highest visual acuity or resolution. Moving outward from the fovea along the retina, there is a progressive decrease in the number of cones, and at 10^o from the fovea, cone density is very low and remains so continuing outward (Wandell, 1995). At 20^o, spatial resolution is reduced to a tenth of what it is within the 2^o of the fovea (Land & Tatler, 2009). The peripheral visual field consists mostly of photoreceptors called rods that reach a peak density at around 10 to 20^o (Wandell, 1995). Rods are highly sensitive to light, but not color, and are the only photoreceptors that detect light in low lighting situations. In the periphery, images are still discernable and features detected by this area are crucial for guiding where to look next (Weib et al., 2014), in particular, during walking.

A full view of our surroundings during walking ensures that we are able to plan our route, monitor our movement, avoid any hazards, maintain balance, and make appropriate stepping corrections (Warren et al., 2001; Logan et al., 2010; Warren et al., 1996). To assess our movement in the environment, vision plays a crucial role in monitoring self-motion (i.e., walking speed) in conjunction with vestibular and proprioceptive inputs (Gibson, 1950; Gibson, 1958; Warren 1998). The main source of visual information that indicates self-motion from the environment is optic flow, defined as the change of the appearance of light on the retina resulting from relative motion between the eyeball and the visual environment (Raudies, 2013). The influence of optic flow on walking is clear from a number of studies where the manipulation of optic flow rate led to a change in walking speed, and the speed at which the walk-to-run transition occurred (Pailhous et al., 1990; Prokop et al., 1997; Konczak, 1994; Mohler et al., 2007). Several studies suggest that both central and peripheral vision are important for the detection of self-motion while walking under conditions of varying optic flow directions (Bardy et al., 1999). These findings support the “retinal invariance” hypothesis that postural adjustments made in response to changes in self-motion detected by optic flow during walking are very similar, regardless of whether they are detected by central or peripheral vision. Judging one’s heading, or direction of movement while walking, seems to also be detected in both central and peripheral vision (Crowell & Banks, 1993, 1996; Warren & Kurtz, 1992). However, conflicting evidence indicates that optic flow is used more by central vision to guide walking, while peripheral vision is more important for updating our representation of the surroundings for navigation (Turano et al., 2005). This is evident in those lacking peripheral vision who are less able to attain an adequate representation of the entire environment and less able to judge the position of distant landmarks (Rieser et al., 1992, Turano et al., 2005). In summary, central vision is essential for creating a high-resolution image of objects of interest and is important for assessing self-motion during walking. Peripheral vision is also important for assessing self-motion, but is more important for evaluating our environment for navigation, and guiding eye movements to relevant objects in the periphery, and monitoring ground terrain and obstacles near the feet while walking (Marigold, 2008).

Given the important roles central and peripheral vision have during walking it is not surprising that those with eye diseases may experience difficulties with many daily activities, including those related to mobility (Swenor et al., 2013). Knowing the crucial role peripheral vision plays during walking it follows that glaucoma, a disease that preferentially degrades peripheral vision, would challenge a walker’s ability to assess self-motion and navigate in their environment. These issues are particularly pertinent to cluttered environments we negotiate every day. With healthy eyes we obtain the information we need to successfully navigate an environment through a series of goal-directed eye and head movements called gaze-behaviour.

1.4. Gaze behaviour for guiding movement

1.4.1. Eye-head coupling

Gaze shifts (when the line of sight is changed in space) that constitute our gaze behaviour are accomplished through coordinated head and eye movements (Bizzi et al., 1971; Bizzi et al., 1972; Bizzi et al., 1972b). To reposition gaze on a new location the eyes rapid rotation starts before head rotation even though the neural command to rotate the head is generated first (Freedman, 2008). After eye rotation has finished, the head continues to rotate, aligning the face with the new gaze location, while the eyes rotate in the opposite direction at a similar velocity to the head (Freedman, 2008). The relative contribution of eye and head rotation to a gaze shift and their timing relationship depends on the predictability of the target, the amplitude of the gaze shift, the initial eye position within the orbit, the predisposition to move the head, and the task requirements (Barnes, 1979; Bizzi et al., 1972; Fuller, 1992; Freedman, 2008; Guitton & Volle, 1987; Stahl, 1999). The amplitudes of head and eye movement respectively are always coupled, despite minor changes in their timing relationship or kinematics (Freeman, 2008). The neural control systems that cause eye movements, and keep gaze fixed while the head moves are intricate, but well-defined.

1.4.2. Neural control of eye movements

The saccadic system shifts gaze to a new location. These eye movements are acted out by a specific set of muscles innervated by a series of neural connections that receive input from a complex array of brain regions. For every eye movement, any of the six extraocular muscles per eye may be used in tandem to move the eye in all directions about three axes of rotation (horizontal, vertical and torsional). Paired contraction of these muscles is essential to move the eyes in a coordinated manner. The medial and lateral rectus muscles produce most of the horizontal eye movements, while the superior and inferior rectus and oblique muscle pairs cause vertical and torsional rotations (Sparks, 2002).

In real-life situations saccades are made to areas that are task-relevant (Marigold & Patla, 2007). Cortical areas that identify the targeted location for saccades include the lateral intraparietal area (LIP) and the supplementary eye field (SEF), which exchange input with the frontal eye field (FEF). The LIP uses information in the form of neural signals from the visual cortex and connects to a main integration center, the superior colliculus (SC). The SC is composed of layers of neurons organized into a retinotopic motor map, where the amplitude and direction of a vector to a visual target are mapped on the two-dimensional sheet of neurons. In conjunction with signals from LIP and the frontal cortex, the inhibitory effects of the basal ganglia on the SC are suppressed, allowing for a saccade. The SC then activates the mesencephalic and pontine reticular formation to produce signals to make a saccade. The brainstem circuitry of horizontal saccades is well described, involving the medial vestibular nucleus, abducens nucleus, nucleus prepositus hypoglossi, paramedian pontine reticular formation (PPRF), nucleus of the dorsal raphe, and the oculomotor nucleus (Kandel et al., 2000). All of these areas interact to activate or suppress cranial nerves III (oculomotor) and VI (abducens) that innervate the medial and lateral rectus muscles.

Two distinct components are involved in a saccade motor signal, the pulse and the step. The position and velocity of the eye are directly proportional to the discharge frequency of the extraocular motor neurons (Kandel et al. 2000). To overcome the viscous drag of the eye and to rotate it as quickly as possible to a new location, the eye velocity can rapidly go from 0^{o} /s to 900^{o} /s with an increase in neuron firing frequency, called the pulse. To then maintain the eye position for a short time, firing frequency is decreased dramatically, but proportional to horizontal eye position, a pattern called the step (Sparks, 2002). The two components each rely on the activity of distinct neurons in the circuit.

The neurons that bring about the pulse component are the burst neurons, which are located in the PPRF. Burst neurons work antagonistically with omnipause neurons located in the nucleus of the dorsal raphe. The latter inhibit contralateral burst neurons and constantly fire except around the time of a saccade in order to maintain eye position and prevent unwanted saccades. After a saccade is made, the eye would naturally return to its original position were it not for the tonic firing of neurons from the nucleus prepositus hypoglossi and the medial vestibular nucleus. They have a firing rate proportional to the horizontal eye position, comprising the step component of the saccade.

Although saccades will rapidly bring areas of interest into the most focused part of our vision, another system allows us to track objects as we move and/or the objects move in the environment. The smooth pursuit system tries match the rotation of the eye to the velocity of the object it is fixating, and therefore is not initiating the rapid eye movements seen in saccades. However, much of the circuitry for creating motor commands is shared between the two systems (Krauzlis, 2005). The FEF, middle temporal (MT) and medial superior temporal (MST) areas each contribute to smooth pursuit through projections to the dorsolateral pontine nuclei. The caudal FEF signals the motor command and initiates the pursuit movement, while the MT and MST calculate the velocity of the target (Fukushima et al., 2011). MT and MST increase their firing until the difference in speed between the eye and object is zero (which is rarely achieved), and then maintain that rate until a new area of focus is chosen. Neurons in the dorsolateral pontine nuclei then project to the flocculus and vermis of the cerebellum, then onto the medial vestibular nucleus and nucleus prepositus hypoglossi. From there, the signal for eye movement velocity is sent to the PPRF, abducens nucleus and ocular motor nuclei in the midbrain. The brainstem nuclei them activate the appropriate eye musculature.

In order to track objects as we move, smooth pursuit eye movements can be combined with head rotation. The vestibulo-ocular reflex (VOR) is the neural system that directs eye movements while accounting for head turning. In the vestibular system, the semicircular canals that detect information about head angular acceleration send that information via the vestibular nerve to the vestibular nuclei and the nucleus prepositus hypoglossi. For horizontal head rotations the medial vestibular nucleus sends signals to the contralateral abducens nucleus, and the lateral vestibular nucleus sends connections to the ipsilateral oculomotor nucleus. Excitation of the contralateral abducens nerve and the ipsilateral oculomotor nerve will then cause eye rotation in the opposite direction to head movement of equal amplitude for both eyes. The vestibular canal that signals head rotation also sends signals to the medial vestibular nucleus that then inhibits activity of the medial and lateral rectus muscles which would otherwise turn the eye in the direction of head rotation (Kandel et al., 2000). The VOR is also flexible. For instance, the cerebellum can suppress the reflex when we want to track objects with the head and the eyes simultaneously. The VOR, smooth pursuit, and saccade system all work together to create a complex series of eye and head movements, collectively known as gaze behavior, enabling us to gather all the visual information needed to perform any visually guided task, from making a cup of tea, to navigating a busy corridor.

1.4.3. Gaze behaviour in everyday tasks

In everyday tasks we make a series of eye movements to task-relevant areas in order to obtain information from our environment that allows us to accomplish a goal. Eye-tracking technology provides a trace of eye and gaze position, from which the gaze behaviour used to complete a task can be identified. Some of the original tasks that were used to investigate gaze behaviour were sandwich and tea making. During those tasks, we do not uniformly sample the environment, but instead mostly fixate on features of objects that we must interact with or monitor. When making tea, fixations are made almost exclusively to so-called task-relevant objects, such as the kettle, mug and tap (Land, 1999). During this series of saccades and fixations, the hands are manipulating the objects and these two sets of movements (eye and hand) are tightly linked. Research into the relationships between gaze behavior and limb movements shows that people shift their fixation multiple times to locations where the hand and an object interact, or where two objects relevant to the task interact (Angel et al., 1970; Johansson et al., 1999; Land 1992; Neggers and Bekkering 1999). For instance, during tea-making gaze was directed to relevant locations about a half a second before manipulating the object at that location with the hand (Land et al., 1999). Similarly, when reaching to grasp a bar to move it to press a target-switch, participants made saccades to distinct points, and did not saccade to the next position until the hand reached the current desired position (Johansson et al., 2001). In addition, during motor tasks gaze often precedes limb movement in a predictive manner, allowing visual information to be used both online to assess the state of current movements, and in a feed-forward manner to plan future movements (Hayhoe et al., 2012). During locomotion in natural environments, much like fine motor tasks, we rely heavily on vision to analyze and predict the state of our surroundings in order to guide foot placement and whole-body trajectory when navigating towards a goal.

1.4.4. Gaze behaviour in walking

Monitoring the gaze behaviour of participants walking in cluttered environments highlights the importance of visual input for path navigation and precision stepping. In route planning, visual information is used to guide path selection towards paths where safe corridors are found and clusters of obstacles are avoided (Patla et al., 2004). When people received visual cues to alter their walking trajectory, they made saccadic eye movements and head rotations to align gaze with the new goal location of the travel path as soon as the cue was given (Hollands et al., 2002). In this way, gaze leads head and body movement during walking. Indeed, when finding the way past obstacles, people tend to fixate most on the end goals they are walking towards, and on objects that make up the border of the path they choose (Patla et al., 2007). Clearly, where we look serves to help align us with our goal. Also, gaze allows us to identify obstacles to avoid. While walking in a crowded corridor, participants looked more frequently at the individuals who exhibited a greater probability of colliding with the participant (Jovancevic-Misic and Hayhoe, 2009).

In addition to changing body trajectory to walk around an obstacle, stepping over an obstacle is a common avoidance strategy that further highlights the importance of vision (Patla & Vickers, 1997). Participants gaze behaviour suggests that eye movements are used to gather important obstacle information for feed-forward planning. During this task, gaze is generally directed 2-3 steps ahead, with higher obstacles being fixated more frequently and often followed by fixations on the ground just past the obstacle to identify the foot landing location. Vision is also important during the approach phase when stepping over an obstacle, as participants can still perform the task, but with much less precision when vision was occluded during this approach phase (Mohagheghi et al., 2004). Interestingly, Franchak and Adolph (2010) found that when children and adults had to find objects (i.e., stars) in a room, they swiftly and effectively navigated many obstacles by stepping up, down, over or around them, making very few fixations to obstacles or footfall areas. The researchers estimate that only 15-32% of obstacles the adults encountered were fixated on.

Since not all obstacles are fixated on directly or only intermittently (Franchak and Adolp 2010; Patla et al., 2007), it follows that information needed to avoid potentially harmful collisions can be acquired using peripheral vision. Likewise, in a controlled treadmill walking paradigm, participants were equally able to avoid tripping on a suddenly appearing horizontal obstacle while looking two steps ahead versus when they were allowed to look directly at the obstacle (Marigold et al., 2007). These findings again point to the importance of peripheral vision during obstacle avoidance, and downplay the idea that we solely use direct fixations to get past them. Peripheral vision has also been shown to be important for identifying and updating the spatial structure of the environment for navigation, including the floor terrain (Turano et al., 2005). By taking in the whole environment with our peripheral vision we can therefore prioritize fixations on objects in our path that we may want to avoid or pursue.

Differences in ground terrain also necessitate the use of visual feedback to guide foot placement during walking. When the walking surface is varied, people tend to continually sample the environment at transition points where surfaces change (Marigold and Patla, 2007). When stepping to targets while walking on normal ground, a distinct timing pattern of visual sampling with respect to lower limb movement is observed (Hollands et al., 1995). Specifically, a saccade is made to a target at the time the foot is lifted to swing towards that target (Hollands and Marple-Horvat, 2001). When this timing is interrupted by only allowing visual input at certain intervals, some studies show locomotion can become awkward and can lack coordination, while others demonstrate a resilience to interruptions in saccade-foot timing (Hollands & Marple-Horvat, 1996; Hollands & Marple-Horvat, 2001; Laurent and Thomson, 1988). The concept of a temporal link between stepping movements and gaze to a footfall location is crucial for performing precision walking tasks in a natural manner, similar to that of the timing observed between gaze and hand movements during tea-making. In addition to the timing of fixations, the importance of peripheral vision in precision walking tasks is highlighted by findings from a study where the lower peripheral field was blocked and participants compensated by tilting their heads down, slowing their walking speed and decreasing their step length to walk over varied terrain (Marigold and Patla, 2008). These important temporal connections between gaze and movement, and the use of peripheral vision during walking can be disrupted by a number of factors, most notably aging and age-associated eye diseases.

1.5. Age-related Low Vision and Mobility

As we age, there is a natural decline in performance on clinical measures of visual function, including visual acuity and visual fields (Rosenbloom, 2006). Although this change is normal, it negatively affects mobility and gaze behavior. In addition, declines in vestibular, muscular, and proprioceptive function, as well as in cognitive abilities lead to increased challenges when walking in complex environments. Corrective lenses can also cause problems, such as refractive blur from multifocal lenses and the associated decrease in contrast sensitivity, which reduce stepping accuracy (Black et al., 2014). In a precision walking task, research shows that older adults look away from stepping targets sooner relative to making foot contact on the target compared to younger adults. The authors hypothesized that older people are more anxious about future steps, resulting in more missteps (Young and Hollands, 2010). Not surprisingly, older people at a higher risk for falls show greater abnormal gaze timing patterns. Specifically, they look away sooner with respect to heel contact with the ground compared to older adults at a lower risk for falls, and as a result, are less precise with their steps (Chapman and Hollands, 2006). Moreover, when navigating around a vertical pole, older adults used a more balance-cautious strategy by looking down at their feet, while young adults looked straight ahead and past the obstacle (Paquette and Vallis, 2010). Older adults at high risk for falls also look down much closer to their feet than young adults when stepping to a series of targets (Yamada et al., 2011). The presence of eye disease, in addition to age-related changes can severely degrade the quality of vision and put older adults at an even greater risk of falling.

1.5.1. The Effects of Low Vision on Lifestyle and Mobility

Low vision is defined as uncorrectable vision loss that interferes with daily activities (Massof & Lidoff., 1999), and includes individuals with AMD or glaucoma. In fact, people with glaucoma are half as likely to leave their home on a given day (Ramulu, 2014). People with advanced AMD most commonly report reading and driving difficulties, and people with glaucoma most commonly report difficulty with lighting and walking (Nelson et al. 1999; Rovner & Casten., 2002). Dim lighting conditions can also have stark consequences on the mobility of people with AMD, leading to increased foot placement errors during precision walking (Alexander et al., 2014). Not surprisingly, limitations in every-day life activities reduce employment rates, as Americans with uncorrected visual impairment are 3 times more likely to be unemployed (Sherrod et al., 2014). Fear of falling is one of the major reasons why people with low vision stay at home more and stop working. This is also associated with higher rates of depression, and thus, all facets of a person's life can be negatively affected by low vision from either of these diseases (Popescu et al., 2012).

While central vision loss affects many aspects of daily life, age-related eye diseases causing peripheral visual field loss such as glaucoma, are found to affect mobility most severely (Popescu et al, 2011; Swenor et al., 2015). Visual field deficits in both eyes that are common to glaucoma affect a wide range of mobility tasks from precision stepping to path navigation to stair climbing, leading to slower walking, more obstacle collisions, and more falls (Friedman et al., 2007; Hassan et al., 2007; Marigold & Patla 2008; Ramulu, 2009; Turano et al., 2005; Viswanathan et al., 1999; Wang et al., 2012). Research shows that people with bilateral glaucoma and reduced visual fields walk significantly slower and experience an increased number of obstacle collisions when walking an obstacle course compared to healthy controls (Friedman et al., 2007). Primary open-angle glaucoma is also significantly associated with injurious falls (Tanabe et al., 2012). For instance, Black and colleagues (2011) reported that 44% of people with glaucoma who were surveyed experienced a fall, and 31% experienced falls that resulted in injury. In addition to mobility problems, people with visual field loss are also more likely to be placed in a nursing home, and develop depression (Bramley et al., 2008).

1.5.2. Mobility and Adaptive Gaze Behavior with Low Vision

People that have glaucoma cannot see the environment in the same way as a healthy person. In severe cases, they can only see a few degrees around their fixation point. In order to perform tasks that normally require peripheral vision it follows that people with visual field deficits would have to scan their environment more extensively. The question arises then, are people with decreased visual fields utilizing compensatory eye movements to help them perform tasks, or are they inadequately scanning the environment, leading to cautiousness and decreased mobility performance?

When viewing a virtual driving scene, glaucoma patients made significantly more saccades overall, but had several incidences where they missed hazards entirely due to their binocular visual field deficit (Crabb et al., 2010). Indeed, when people with glaucoma scan an image, they make more eye movements, but cover less of the total image (Smith et al., 2012). These inadequate visual behaviors provide an indication as to why hazards were missed in the virtual driving task, and are missed in everyday life (Crabb et al., 2010; Smith et al., 2012).

Individuals with Retinitis Pigmentosa (RP), a family of diseases with similar visual field deficits to glaucoma, appear to scan the environment differently when walking than those with normal vision (Turano et al., 2001). People with RP made more saccades overall, and tended to look down, at the walls, at task irrelevant objects, and at edge-lines between walls when walking through a corridor (Turano et al., 2001). In contrast, healthy subjects largely focused their gaze on the goal they were walking toward (Turano et al., 2001). Clearly, this eye disease causes modified gaze behavior whereby people search more of the environment that is not task-relevant, which the authors hypothesized to be a result of their uncertainty of what lies in their peripheral vision (Turano et al., 2001). However, Geruschat and colleagues (2006) found that during street crossing, people with glaucoma did not show large differences in gaze patterns compared to healthy older adults. This finding is important because it indicates that people with glaucoma do not appear to have very different gaze patterns resulting from their eye disease in settings where precise foot placement or path navigation is not required and the risk for falling is relatively low.

The gaze behavior of people with glaucoma in a natural and complex walking environment is unknown, and even less understood are the gaze behaviours that might improve their mobility. These behaviours have been identified to a limited extent in groups of people with vision losses in distinct areas of the visual field. Certain people with homonymous visual field defects (vision loss on the same side in both eye) due to brain lesions show gaze behaviors leading to higher performance when moving through a virtual walking environment (Papageorgiou et al., 2012). Based on task performance, subjects were split into two groups, adequate and inadequate performers. The visual behaviours that made adequate performers successful were increased exploratory head and eye behaviour, particularly towards moving objects of interest in their blind side. These findings imply that gaze behaviours that compensate for vision loss may exist for other visual field deficits as well. These should extend to conditions where a person is walking, as walking itself is shown to modify gaze behavior in people who have low vision. For example, people with unilateral cortical blindness used adaptive gaze strategies during a visual tracking task and performed just as well as controls while seated or during quiet stance (Iorizzo, et al., 2011). However, these gaze strategies were completely lost while walking, resulting in massive deficits in visual tracking ability (Iorizzo et al., 2011). These findings highlight the effects that the physical and cognitive demands of walking itself have on visual performance for people with low vision. Despite the lack of information on how gaze behaviors affect mobility in people with low vision, some researchers have attempted to use visual training paradigms to improve mobility, albeit with limited success (Kuyk et al., 2010).

Research on visual training has had some success in healthy eyed people at a higher risk for falling. By training older subjects to fixate longer on the target they are stepping to with respect to when the foot lands on the target, Young and Hollands (2010) were able to reduce the side-to-side error of foot placement on targets. This is important because this measure is linked to a higher risk of falling (Yamada et al., 2011). Less effective however, are visual training paradigms in those with low vision. In an attempt to modify subject’s gaze behavior to improve mobility, Kuyk and colleagues (2010) trained people with visual impairments to improve search speed and search accuracy in the presence of distracters on a computer monitor. After training, there was no difference in speed to complete an obstacle avoidance walking task, and there were minor improvements in obstacle contacts, but only in low lighting conditions. This suggests that deficits in search speed and accuracy are not the only causes of mobility problems with low vision. Further research connecting gaze behavior and mobility is needed to design combined mobility and gaze training for people with low vision (Young and Hollands, 2010). Also, because of the varying nature of low vision, gaze strategies may be specific to each eye disease and therefore require disease-specific gaze training. For example, it is known that loss of the lower peripheral visual field compared to the upper field is associated with higher rates of falls and injury (Black et al., 2011). It should therefore be extremely important to compensate for loss of this area of the visual field with head and eye movements during walking. Understanding the gaze strategies that are specific and beneficial to those with glaucoma during walking will provide the basis for gaze training that will reduce the devastating effects of progressive vision loss on a person's lifestyle. Gaze-mobility training will aid in safer walking, but should also apply to situations where the walking task is not the only focus of attention. Often, our attention is divided during walking, for instance when looking for a particular landmark or having a friendly conversation. The subsequent effects of divided attention on gaze behavior and walking performance must therefore be evaluated to increase the generalization of gaze-mobility training to real-world situations.

1.6. Dual tasking

In everyday walking situations we often carry out a conversation and/or search for landmarks while regulating and modulating our stepping, all of which require some of our attention that unfortunately is not limitless. Working memory is the system that stores and integrates information related to cognitive tasks over a short time frame and is active during walking that demands attention (Baddeley & Hitch, 1974; Baddeley, 1986; Baddeley, 1992). Working memory capacity depends on many factors including the nature of the task (Kane & Engle, 2003). There is a complex relationship between central attention and working memory that is not fully understood, but they both contribute to overall visuospatial attention (Fougnie, 2008). The processes that allow us to navigate, when combined with a simultaneous secondary task (dual tasking), may overload our visuospatial attention capacity. According to the capacity-sharing theory, performance on either one or both tasks should decrease if attention capacity is exceeded (Tombu & Jolicoeur, 2003; Yogev-Seligmann et al., 2008). Depending on the nature of the two tasks, this performance decrease can be due to the simultaneous use of the same physical structures in the two tasks (structural interference), or to limited central attention capacity (capacity interference) (Salthouse, 1975).

1.6.1. Dual tasking during walking in young adults

Although walking and dual tasking may seem simple to young healthy people, evidence of costs to either walking or the secondary task is abundant. For instance, during level ground walking and stair climbing while dual tasking, gait speed and gait mechanics are negatively impacted in young adults (Springer et al., 2006; Vallabhajosula et al., 2015). Interestingly, the differences are larger for a cognitive secondary task (subtracting numbers) compared to a physical one (holding a box), showing that competition for working memory and attention can exist between two tasks that may not necessarily both involve movement. During walking and counting backwards, functional near infrared spectroscopy imaging shows an increase in activity in the frontal lobe compared to counting backwards while standing (Mirelman et al., 2014). However, Kline et al (2014) demonstrated that despite detecting changes in brain activity when performing a spatial recognition dual task while walking at different speeds, secondary task performance was not decreased. In another study in which young adults walked while performing various secondary tasks, the type and perceived level of difficulty of the cognitive task impacted costs for cognitive and mobility performance (Patel et al., 2014). Also, when subjects were allowed to adjust their gait speed during dual tasking, all dual task costs were eliminated (Grubaugh & Rhea, 2014). These collective findings suggest that small effects are seen on walking tasks for young adults and effects are larger for secondary tasks, but that this relationship depends on the nature of the secondary task and the attention capacity or cognitive function of the individual. Since aging causes a decline in motor and cognitive function, it is likely that dual task costs for motor and cognitive tasks are greater for older adults than young adults.

1.6.2. Dual tasking and walking in old adults

Research on the mobility performance of older adults during dual tasking is rightfully receiving a lot of attention in recent years, as changes in step width, step time, and step-length found during dual tasking are some of the best indicators of increased fall risk (Hirashima et al., 2015; Nordin et al., 2010). Aging is associated with cognitive decline that leads to a decrease in working memory capacity (Beurskens & Bock, 2012; Persson et al., 2006; Salthouse, 2009). The effects of reduced working memory are evident during over ground walking while dual tasking, as healthy older adults and those in need of care show decreases in gait speed and cadence, as well as higher stride length variability compared to young adults (Agner et al., 2015; Priest et al., 2008; van Iersel et al., 2007; Verghese et al., 2007). In addition, older adults have greater mediolateral upper trunk movement that increases when dual tasking, supporting their augmented risk of injurious falls (Asai et al., 2013). This trend extends to many other walking tasks as well. Indeed, when stepping over an obstacle that appeared on a treadmill, healthy older adults have high avoidance task failures and slower response times in dual tasking conditions (Hegeman et al., 2012). Moreover, during stair descent while dual tasking, older adults walk slower, have higher foot clearance (are more concerned with tripping) and greater dual task costs (Telonio et al., 2013). In dual task walking, decreases in walking performance are problematic because as gait speed slows, gait variability increases in measures related to falls, such as stride-length and stride time (Hausdorff et al., 2008).

An encouraging finding is that during simple dual tasks, older people, like young people tend to prioritize the motor task, especially as it becomes more challenging. This suggests that safety is a higher priority (Kelly et al., 2013). However, as the difficulty of the dual task increases, older people seem to prioritize the dual task over the motor task, increasing fall risk (Verghese et al., 2007; Bloem et al., 2001; Springer et al., 2006; Yogev-Seligmann et al., 2010). Prioritization of tasks can be modified for older individuals by instructing them to focus on the cognitive or walking task, but older adult’s ability to prioritize is less flexible than young adults (Yogev-Seligmann et al., 2010). Interestingly, the type of dual task impacts prioritization as well (Kelly et al., 2013). For example, Bock and Beurskens (2011) observed that dual task interference is similar for young and old people when the non-walking task does not require the processing of visual information. However, it is not surprising that dual-task interference is more pronounced in older compared to young subjects when the non-walking task requires continuous visual processing abilities, which decline with age. (Bock and Beurskens, 2011). This raises questions about how people with low vision handle dual tasking when walking, particularly when distracted by a secondary task.

1.6.3. Dual tasking and walking with low vision

Investigation of the effect of any sort of low vision on dual task performance is extremely limited. However, walking is less safe while dual tasking for older people, and given the prevalence of eye diseases associated with old age, this is an important area of study. In addition, recent research shows that those with low vision due to AMD, Fuch’s corneal dystrophy, or glaucoma have lower cognitive scores on the mini mental state test (Harrabi et al., 2015). Why this occurs is unknown, but these findings further suggest those with low vision may have more problems during dual tasking and walking.

When standing, people with AMD exhibit greater instability when performing a mental secondary task, and this is exacerbated while standing on foam (Kotecha et al., 2013). Standing on foam and performing the secondary task also causes increased postural instability in those with glaucoma (Kotecha et al., 2013). While reaching and grasping to a target with a secondary counting task, people with macular disorders and control subjects showed slowed onset to reach time, but those with visual impairment also had online reaching corrections disrupted by dual tasking (Pardhan & Zuidhoek, 2013). This evidence shows that visual disorders cause additional performance detriments during dual tasking involving visually guided movement. It is known that dual tasks that require high amounts of visual attention during walking lead to greater impairment in the young and elderly. Thus it follows that restricted visual fields lead to even greater mobility costs (Bock, 2008; Miyasike-daSilva & McIlroy, 2012). Yet, during walking with simulated low vision using blurred goggles, neither young nor older adults showed any significant differences in gait speed or step length during dual tasking (Deshpande et al., 2015). Similarly, older adults that had vision of their feet obstructed during walking and dual tasking did not show differences in gait speed, step duration, leg rotation, step consistency, or missed steps compared to when they had full vision (Bock & Beurskens, 2010). However, neither study had subjects perform complex walking tasks. As such, it is not surprising no differences were found. Research has shown that older adults require vision of their foot placement when walking on varied terrain or when stepping to targets (Chapman & Hollands, 2006; Marigold & Patla, 2008). Collectively, studies in this area involving older adults with reduced visual fields have not answered the question of how dual tasking affects mobility performance in complex walking tasks and how this relates to gaze behavior. Both of these aspects are investigated in this thesis.

1.7. Research Aims and Hypotheses

People with glaucoma experience difficulty with their mobility related to their visual field loss, however the underlying cause is unclear (Friedman et al., 2007; Nelson et al., 1999; Ramulu, 2009; Tanabe et al., 2012; Wang et al., 2012). Visual field deficits lead to altered gaze behaviour in various tasks (Crabb et al., 2010; Smith et al., 2012), but have not been investigated during walking in complex environments. Given the complex and dynamic world we live in, walking is often accompanied by multitasking, which further impacts gaze and/or mobility, particularly in older populations (Agner et al., 2015; Priest et al., 2008; van Iersel et al., 2007; Verghese et al., 2007). Thus, the general aim of this research is to identify how gaze behaviour and mobility are impacted by glaucoma during various walking tasks, how changes in gaze behaviour relate to mobility problems, and how these motor behaviours are altered by dual tasking.

1.7.1. Specific Aim 1

To determine how glaucoma impacts mobility and gaze behaviour, and how these relate to each other during a precision walking task.

The visual field loss that occurs due to glaucoma may impact a person's ability to see the targets well, and as such, may impact their mobility and gaze behaviour. However, compensatory eye movements may allow a person with glaucoma to adequately visually sample their environment and step accurately. This gaze-mobility relationship may also be impacted by the addition of a dual task that requires cognitive and/or visual attention. In this experiment, subjects will step to the center of four stationary targets as they walk.

Precision walking to targets is often used in the research setting to assess the control of foot placement. This task will be performed with no dual task, while performing a counting task, and while performing a visual search task. This study will be the subject of chapter 2.

Hypothesis 1: The control of foot placement will be decreased in older adults with glaucoma compared to age-matched controls when stepping to a series of irregularly spaced targets. Increases in saccade-stepping interval time (e.g., the time interval between saccade onset towards a target and toe-off to step on that target) will be seen in people with glaucoma and will correlate with mobility measures.

1.7.2. Specific Aim 2

To determine how glaucoma impacts mobility and gaze, and how these relate to each other during an obstacle navigation task.

Restricted visual fields that manifest from glaucoma may inhibit one's ability to navigate through obstacles without bumping into them, such as people in a crowd. They may also lead to different gaze behaviour that is linked to these mobility differences. Older adults with and without glaucoma will walk through a series of four vertical poles navigating their way towards a goal at the end of the course. The set-up of this task allows for the identification of mobility, navigational, and gaze differences in people with glaucoma similar to when walking through a crowd. This task will be performed with no dual task, while performing a counting task, and while performing a visual search task. This experiment is addressed in chapter 3.

Hypothesis 2: Walking through vertical poles with glaucoma will lead to increased obstacle collisions and poorer path choice. Glaucoma will also lead to an increased tendency to look near the feet and at poles, which will correlate with mobility deficits.

Chapter 2. Mobility and gaze behaviour during precision walking in people with glaucoma.

2.1. Introduction:

Glaucoma is the leading cause of irreversible blindness and is projected to affect over 100 million people worldwide in 2040 (Tham et al., 2014). Vision loss starts in the periphery and progresses centrally until only a small island of vision remains (Weinreb et al., 2014). Currently, treatments only halt or slow the progression of vision loss, so most people with glaucoma live out their lives without a portion of their peripheral vision (Weinreb et al., 2014). People with glaucoma often report having difficulties with many areas of their lives, including those related to mobility (Neslon et al., 1999). This includes problems with steps, shopping, and crossing the road. As such, people with low vision have a greater fear of falling, and have a higher frequency of injurious falls (Popescu et al., 2012; Tanabe et al., 2012).

Vision plays an essential role in situations where precise control of foot placement is needed, such as when stepping on uneven ground (Marigold & Patla, 2007). This presents a challenge for people with limited peripheral vision since the lower visual field in particular is integral in providing information about limb movement related to the environment (Marigold et al., 2007; Marigold & Patla 2008). With visual field loss due to glaucoma, people walk slower and bump into things more often (Friedman et al., 2007). However, it is unclear how they perform on a precision walking task.

Research has demonstrated that when walking to targets, subjects look to and from targets at specific times with respect to when they step onto them (Hollands et al. 1995). Timing is normally linked such that gaze is directed to a target until foot contact is made with it. Older adults at high risk for falling look away from the target sooner (Young & Hollands. 2010). This behaviour may indicate that they are worried about identifying future footfall locations at the expense of monitoring those relevant to the upcoming step.

Prioritizing gaze towards steps further ahead has been linked to errors in foot placement and unsafe stepping (Young & Hollands. 2010). The greater risk of falling among persons with glaucoma may relate, in part, to poor control of foot placement. This control may relate to changes in gaze behaviour, which this research aims to establish.

In addition to untimely gaze behaviour, multitasking can decrease stepping ability while walking in older adults. When multitasking, working memory capacity may be exceeded, causing costs to performance on one or both tasks. The natural decline in cognitive and physical abilities with aging contributes to mobility limitations, particularly when dual tasking. When multitasking gait speed slows, step length increases, side-to-side trunk movement increases, and performance decreases for obstacle avoidance and stair climbing tasks (Agner et al., 2015; Asai et al., 2013; Beurskens & Bock, 2012; Hausdorff et al., 2008; Hegeman et al., 2012; Persson et al., 2006; Priest et al., 2008; Salthouse, 2009; Telonio et al., 2014; van Iersel et al., 2007; Verghese et al., 2007). The costs of dual task performance often depend on the nature of the tasks. For instance, a simultaneous physical task, such as carrying a box while walking up stairs does not seem to impact walking performance to the same extent a cognitive task like backwards counting does (Vallabhajosula et al., 2015). When walking, our visual attention can be divided between looking where to walk, and looking to other areas of interest in the environment. Not surprisingly, walking performance is decreased in older adults when performing a simultaneous visual search task (Bock & Beurskens, 2011).

The aim of this study was to determine how gaze behaviour and mobility are affected by glaucoma during precision walking under multitasking conditions. To accomplish this aim, older adults with and without glaucoma performed a target stepping task under three conditions: stepping to targets only, stepping while counting backwards by serial threes, and stepping while identifying the sequence of shapes positioned around the walkway. We hypothesized that foot placement error and variability would be higher for people with glaucoma. Furthermore, we hypothesized that they would look to targets more often and to future targets sooner. In addition, we hypothesized that older adults with and without glaucoma would perform worse and show disruption in their gaze behaviour during both dual task conditions, with glaucoma exacerbating these effects.

2.2. Methods

2.2.1. Subjects

Twenty-nine older adults were recruited for this study: 14 had glaucoma (9 men, 5 women; age, 73.6 ± 5.4 yrs) and 15 were healthy-eyed controls (9 men, 6 women; age 70.5 ± 6.3 yrs). There were no significant differences in age (p=0.051). We used convenience sampling, with all glaucoma subjects recruited through a collaborating ophthalmologist, and control subjects recruited through an eye clinic and community centers.

The inclusion criteria were such that participants were 60 years of age or older, able to understand instructions in English, and had best eye visual field mean deviation (MD) scores worse than -2 dB (glaucoma subjects) or worse eye visual field MDs better than -2 dB (control subjects). The exclusion criteria included uncorrected or significant eye disease other than glaucoma (such as cataracts), osteoporosis, a history of cardiac, neurological or musculoskeletal disorders that could affect balance or gait, and a Mini-Mental State Exam (MMSE) score less than 25 (Folstein et al., 1975). The Office of Research Ethics at Simon Fraser University approved the study, and all participants prior to performing the experiments gave written consent.

2.2.2. Ancillary measures of vision and mobility

Visual field scores for glaucoma subjects were obtained at the ophthalmologist's office using a Humphrey systems visual field analyzer (model HFA-II 750; Carl Zeiss Meditec, Inc., Dublin, CA) via the SITA-Fast central 30-2 threshold test procedure (size III Goldmann white target and background luminance of 10.03 cd/m^2). For control subjects a Humphrey systems visual field analyzer (model REF, 710 series; Carl Zeiss Meditec, Inc., Dublin, CA) was used at the lab. This analyzer used frequency doubling technology perimetry, with 10° by 10° targets of varying contrasts made up of black and white vertical sine wave grating of low spatial frequency (0.25 c/deg) undergoing counter-phase flickering at 25Hz. Both forms of visual field analysis are effective for monitoring vision loss with glaucoma (Nouri-Mahdavi, 2014). A mean deviation score in decibels (dB) was used to quantify the amount of visual field loss, where a more negative number indicates a greater area of loss compared to age-adjusted norms. Best-corrected binocular visual acuity was determined using standardized Snellen line examination charts on a SIFIMAV Vision Tester at a distance of 3 meters (Mav-III; SIFI, Italy). Binocular contrast sensitivity was assessed using the Melbourne Edge Test (MET) at a distance of 40 cm (Verbaken & Johnston, 1986). Subjects were required to identify the orientation of an edge in a series of test circles at progressively decreased contrast. Contrast is recorded in decibels (dB) ranging from 1 to 24 dB. The dB value of the lowest contrast patch correctly identified was recorded as a subject's contrast sensitivity. Stereoacuity was measured in seconds of arc using a RANDOT stereopsis test consisting of a series of shapes that may or may not appear to pop out of the screen (Stereo Optical Company, USA). Central vision processing speed, divided visual attention ability, and selective visual attention ability was examined using Useful Field of View software through a series of three subtests at a viewing distance of ~50 cm (UFOV, Version 7.0.2, FL, USA). To determine central vision processing speed, subjects had to identify the presence of either a white car or truck that appears briefly in the middle of the screen. The software decreases the length of stimulus presentation until a subject is able to correctly identify the item 75% of the time. Divided visual attention ability of the subject was assessed using the same central stimulus identification in the center of the computer screen. Here, subjects also had to identify the location of simultaneously appearing car in the periphery at one of eight locations located 15 cm radially from the central stimulus. A similar method where 75% correct responses were given determined the timing threshold for this test. Selective visual attention was also assessed using the same method as divided visual attention test, however 47 triangles were also present on the screen to distract the observer from the location of the radially located car. Scores for all tests are reported in ms, indicating the stimulus duration a subject requires to successfully perform each test 75% of the time.

Mobility function was assessed for each subject using the timed up-and-go (TUG) test. This test required subjects to stand up from a chair, walk 3 m, turn, walk back, and sit down on the chair (Podsiadlo & Richardson, 1991). The TUG was used to evaluate functional mobility of all subjects.

Visual, mobility and cognitive results are outlined in Table 2.1.

Table 2.1: Subject visual scores for glaucoma and control groups

Measure	Glaucoma Group	Control Group	P-value
Best Eye MD (dB)	-9.4 ± 5.7	0.8 ± 1.7	<0.001
Worse Eye MD (dB)	-17.4 ± 7.6	0.2 ± 1.9	<0.001
Binocular Contrast Sensitivity - OU (dB)	16.5 ± 2.0	19.7 ± 1.1	<0.001
Stereopsis - OU (s^{-1} arc)	180.0 ± 120.2	60.7 ± 56.0	0.02
Visual Acuity - OU (log units)	0.09 ± 0.1	0.02 ± 0.1	0.04
Visual Processing Speed - OU (UFOV 1 Score)	67.3 ± 100.7	13.9 ± 1.6	0.04
Divided Visual Attention - OU (UFOV 2 Score)	217.2 ± 187.5	99.9 ± 88.7	0.03
Selective Visual Attention - OU (UFOV 3 Score)	322.9 ± 139.7	186.7 ± 109.3	0.005
MMSE (Score/30)	28.8 ± 0.9	29.5 ± 0.6	0.01
TUG (s)	9.9 ± 2.1	9.0 ± 0.8	0.08

Note: Abbreviation: MMSE = Mini mental state exam; OU = Oculus uterque (both eyes); TUG = timed up & go; MD = mean deviation.

2.2.3. Procedure:

Subjects performed a precision walking task such that they walked and stepped to four sequential targets (30 cm x 15 cm) located on a 6 m walkway without stopping (Figure 2.1). The first target was positioned 1.5 m in front of the subject. The anterior-posterior (AP) distance between the following three targets was 70% of subject's leg length. The positions of targets 2 and 3 were varied such that four arrangements were randomized across trials. Each arrangement varied targets 2 and 3 each by 5 cm in either the AP or medial-lateral direction (ML). This ensured that the task required continuous visual observation to accurately step to the targets, and minimized any learning of target position throughout the duration of the experiment. Subjects always stepped on the first target with their right foot. Vision was blocked before each trial using a wooden board to prevent the subject from seeing the target arrangement until the “go” signal was given. This prevented subjects from relying entirely on a memory of target positions. All subjects wore their habitual vision corrective lenses for the duration of the experiment.

Subjects performed the precision walking task under three conditions that were fully randomized. Each condition had 12 trials, for a total of 36 trials. For all conditions, subjects were instructed to start walking as soon as they heard “go” and the board blocking their vision was removed. They were told to walk at their comfortable speed, to step as accurately as possible to the targets, and not to stop walking until reaching the end of the walkway.

In the “target only” condition, subjects were asked to step to the targets as described above, without performing any additional task. This served as the baseline condition to which measures could be compared to when dual tasking.

In the “counting” condition, subjects were required to count backwards by serial threes from a random two-digit number between 50 and 100. To establish a baseline in performance, subjects performed three trials of the counting task while seated, prior the walking experiment. During the walking task, subjects were instructed to walk while saying as many correct numbers as they could until toe-off from target four. A researcher recorded the number of correct responses given for each trial. The value for baseline counting performance and counting while walking performance were both normalized to the number of correct responses/second.

In the “visual search” condition, subjects were required to identify the sequence of four black (13 cm length, width or diameter) shapes printed on white tiles (20 cm x 15 cm) laid out on the floor. The shapes were a square, circle, triangle and cross. The position of the four shapes on the floor was always the same, but the configuration was altered to one of four randomly selected sequences before the start of each trial (Figure 2.1a). Prior to testing, the shapes were presented in the same manner while the subject stood still. They assessed the shape sequence for 4 seconds (a typical duration subjects could see the shapes during walking based on pilot testing) before having their vision blocked. They were then asked to identify the position of one randomly selected shape. This was repeated 12 times, and the number of correct responses (out of 12) represented a baseline in visual search performance. When performing the visual search dual task, subjects were asked to walk as described above, while identifying the positions of the shapes. After taking two steps past the fourth target, subjects stopped so they could not see the walkway, and were asked to identify the position of one randomly selected shape. The number of correct responses represented each subject’s dual tasking visual search performance.

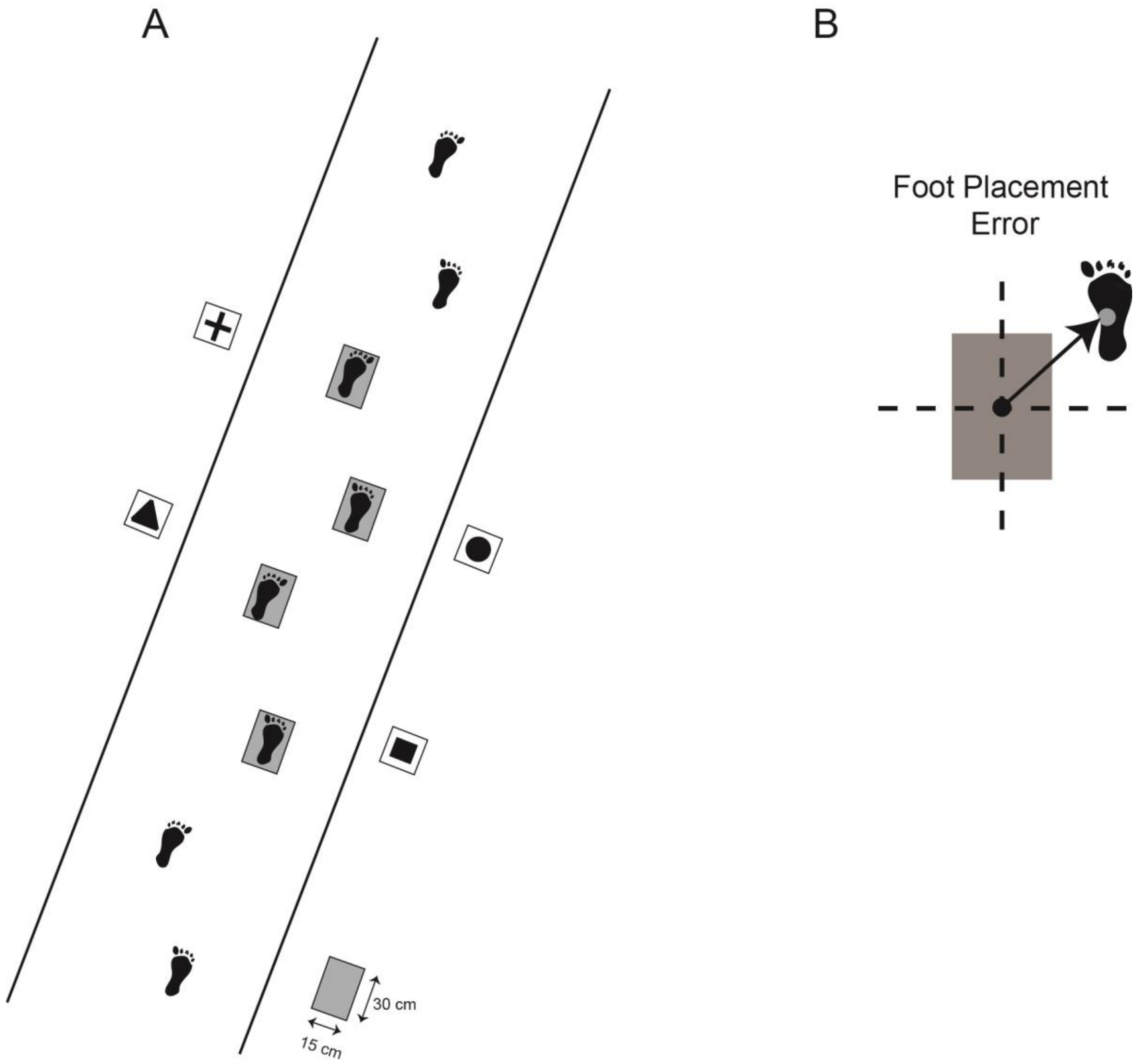


Fig 2.1: Precision walking task set-up (A), and foot placement error diagram (B) are shown. AP target distance was scaled to 70% of subject's leg length. Visual search task shapes were only present during the visual search condition.

2.2.4. Data and Statistical Analysis

Kinematic measures were obtained by recording, at 120 Hz, the position of motion-capture markers of an Optotrak Certus system (Northern Digital, Ins., Waterloo, Canada) located on the head, chest, and bilaterally at the forefoot, mid-foot and heel. All kinematic data were interpolated using a Butterworth low pass filter at 6Hz in a custom MATLAB program, and then analyzed using custom-written LabVIEW (National Instruments, Austin, TX) programs.

Mobility performance for each condition was measured using foot placement vector error for all targets. This was defined as the average end-point distance of foot placement (using the position marker at the mid-foot) from the center of the target, and was averaged across the four targets and then trials (Figure 2.1b). Foot placement error variability was defined as the variability (standard deviation) across targets and trials in foot placement vector error. Gait speed was recorded as an auxiliary measure using the time it took the chest marker to move from target one, to target four, divided by that AP distance.

Gaze data were recorded using Applied Science Laboratories (Bellerica, MA, USA) high-speed head-mounted eye tracking system, which tracks the rotations of the left eye at 120 Hz. The software produces a gaze location in 2-dimensional coordinates on the ground, as well as on a 30Hz video with gaze position being represented by the intersection of vertical and horizontal cross hairs. Gaze data were filtered using a Butterworth low pass filter at 6Hz in a custom MATLAB program. Head rotation velocity in room coordinates obtained from a two-sided Optotrak rigid-body was subtracted from gaze rotation velocity in room coordinates on the floor (using gaze location in Optotrak coordinates, produced by ASL software) in 3 dimensions, in order to extract eye rotation using a custom MATLAB program. Saccade start and end times were then identified using a custom LabView program. Saccade and fixation times were identified using gaze data recorded at 120 Hz, while area of interest (AOI) classification was done using 30 Hz video. We defined saccades as instances where eye rotation exceeded 100 degrees/s (Chapman & Hollands, 2006) and returned below this value. The location of gaze was then identified by looking at the 30 Hz video of the walkway with gaze coordinate crosshairs. Fixations were denoted when stable gaze was on one AOI for > 67 ms (Turano et al., 2001), which was either a target or a shape (where applicable). Fixation duration was expressed as the time when a saccade was made away from an AOI minus the end time of the saccade toward that AOI. Saccades made within the same AOI before gaze was shifted away from it were included in AOI fixation time. The kinematic measures for heel contact and toe-off were obtained using a custom LabVIEW program, and defined for each step as the local maximum vertical acceleration of the heel, and the local maximum horizontal acceleration of the toe, respectively (Hreljac & Marshall, 2000).

Gaze behaviour was assessed for each condition using 6 measures. Four were normalized to trial length before being averaged across trials. These included; the number of fixations on targets for each trial, the number of times the same target was fixated (re-fixations), the average duration spent looking at the targets in a given trial, and the total time spent looking at targets for a given trial. The other two measures were saccade – heel contact latency, defined as the time a saccade was initiated away from a target minus the time heel contact was made with that target, and saccade – toe-off latency, defined as the time a saccade is initiated toward a target for the first time minus the time toe-off is made for stepping to that target. Gaze data was filtered using a Butterworth low pass filter at 6Hz in a custom MATLAB program. Head rotation velocity in room coordinates obtained from a two-sided Optotrak rigid-body was subtracted from gaze rotation velocity in room coordinates on the floor (using gaze location in Optorak coordinates, produced by ASL software) in 3 dimensions, in order to extract eye rotation using a custom MATLAB program. Saccade start and end times were then identified using a custom LabView program. Saccade and fixation times were identified using gaze data recorded at 120 Hz, while area of interest (AOI) classification was done using 30 Hz video. We defined saccades as instances where eye rotation exceeded 100 degrees/s (Chapman & Hollands, 2006) and returned below this value. The location of gaze was then identified by looking at the 30 Hz video of the walkway with gaze coordinate crosshairs. Fixations were denoted when stable gaze was on one AOI for > 67 ms (Turano et al., 2001), which was either a target or a shape (where applicable). Fixation duration was expressed as the time when a saccade was made away from an AOI minus the end time of the saccade toward that AOI. Saccades made within the same AOI before gaze was shifted away from it were included in AOI fixation time. The kinematic measures for heel contact and toe-off were obtained using a custom LabVIEW program, and defined for each step as the minimum vertical acceleration of the heel, and the minimum horizontal acceleration of the toe, respectively.

Dual task performance was evaluated based on performance “costs”. This was calculated by dividing the average counts/second during dual tasking by the baseline counts/second value, and similarly by dividing the number of correct shapes/12 trials during dual tasking by the baseline value. Gaze behaviour with respect to the visual search shapes was analyzed using four measures; number of fixations to shapes, re-fixations to shapes, average fixation duration per shape, and total fixation duration on shapes. All four were obtained per trial, normalized to trial length, and averaged across trials.

Statistical analysis was done using JMP 11 (Cary, USA) software with an α-level of 0.05. Differences between groups (glaucoma and control) and across conditions (target only, counting, and visual search) for all mobility and gaze measures were identified using two-factor (Group x Condition) ANOVAs. Tukey's post hoc tests were used to identify differences between levels when ANOVAs showed significant results. The relationship between mobility/gaze measures and visual field loss were examined using linear regression analysis to test if slopes were significantly different from zero for each measure and best eye MD individually, and then tested for differences between slopes using a one-way ANOVA. The presence of significant dual task costs were evaluated using a one-sample t-test comparing cost to a value of 1 (no cost), and dual task cost differences between groups for the counting and the visual search measures were analyzed separately using paired t-tests. Lastly, to identify difference in gaze behaviour to the visual search shapes between groups, a one-way ANOVA was used.

2.3. Results:

2.3.1. Precision walking task group and condition differences:

Mobility:

The precise control of foot placement when walking to four targets was investigated under three different conditions for people with and without glaucoma.

Analysis of gait speed showed evidence of a Group x Condition interaction ($F_{2,53} = 4.60$, $p = 0.014$). Post hoc tests revealed that gait speed was similar for both groups, but slower for those with glaucoma in the counting dual task condition. Gait speed did not correlate with accuracy for either group in any condition, and therefore was not included as a covariate in further analysis. Foot placement was impaired for people with glaucoma compared to controls, and this was exacerbated during both dual task conditions. This was evident in the mean values for the groups in each condition (Fig. 2.2). The ANOVA revealed that for foot placement error there was a main effect of group ($F_{1,27} = 8.24$, $p = 0.008$) and condition ($F_{2,53} = 5.39$, $p = 0.007$). Post hoc tests indicated that older adults with glaucoma performed worse than controls, and that performance was worse for both groups in the counting and visual search conditions compared to the target only condition (Fig. 2.2a). Similarly, the ANOVA foot placement error variability showed a main effect of group ($F_{1,27} = 4.29$, $p = 0.048$) and condition ($F_{2,53} = 4.05$, $p = 0.023$), with post hoc tests revealing the glaucoma group had more stepping variability compared to the control group, and that variability was greater during the visual search task than the target only task (Fig. 2.2b).

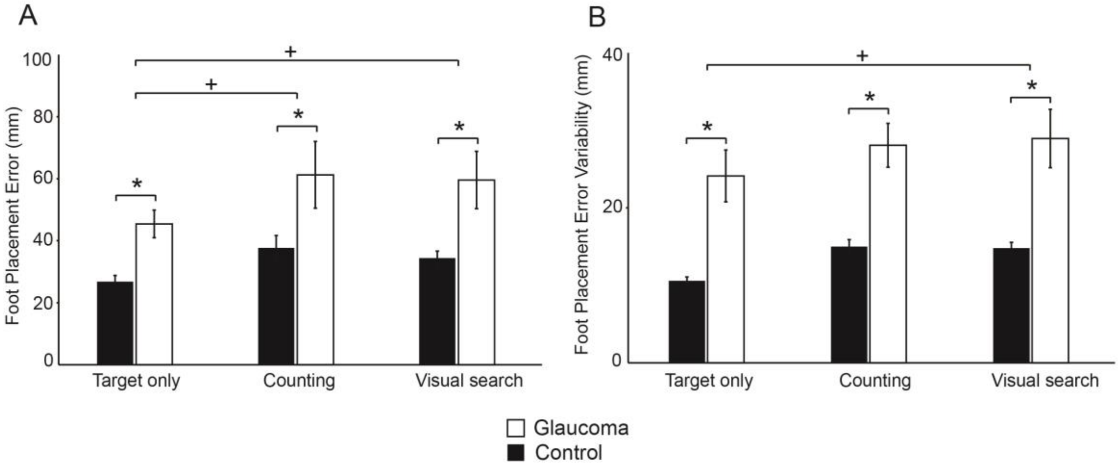


Figure 2.2: Mean (+/- SE) vector foot placement error (A) and foot placement error variability (B) across groups and conditions are shown. Significant group (*) and condition (+) main effects are indicated.

Gaze Behaviour:

The characteristics of gaze behaviour for glaucoma and control subjects to areas of interest (targets and shapes, where applicable) were examined during precision walking. For most measures, gaze behaviour differed between the glaucoma and control groups, and depended on the dual task condition. The differences in mean values for number of target fixations are shown in Figure 2.3a. An ANOVA exhibited a significant main effect of condition on the number of fixations on targets per trial ($F_{2,52} = 15.47$, $p < 0.0001$), such that when counting, both groups made significantly fewer fixations to targets. In addition, there was a main effect of group ($F_{1,26} = 12.9$, $p = 0.001$) and condition ($F_{2,52} = 19.8$, $p < 0.0001$), where those with glaucoma re-fixated to the same target more often than controls, and more fixations were made for both groups during the visual search dual task compared to the other conditions (Fig 2.3b).

Main effects of group ($F_{1,26} = 9.88$, $p = 0.004$) and condition ($F_{2,51} = 31.16$, $p < 0.0001$) were also seen for the average fixation duration on targets, with post hoc tests showing that the glaucoma group had a shorter average fixation duration than controls. During the visual search condition, average fixation duration was less than for the other dual task conditions (Fig 2.3c). In addition, total fixation duration on targets for a given trial differed between conditions ($F_{2,51} = 30.06$, $p < 0.0001$) (Fig 2.3d). Further analysis showed that total fixation duration was greatest during the target only task, less during the counting task, and even less still during the visual search task.

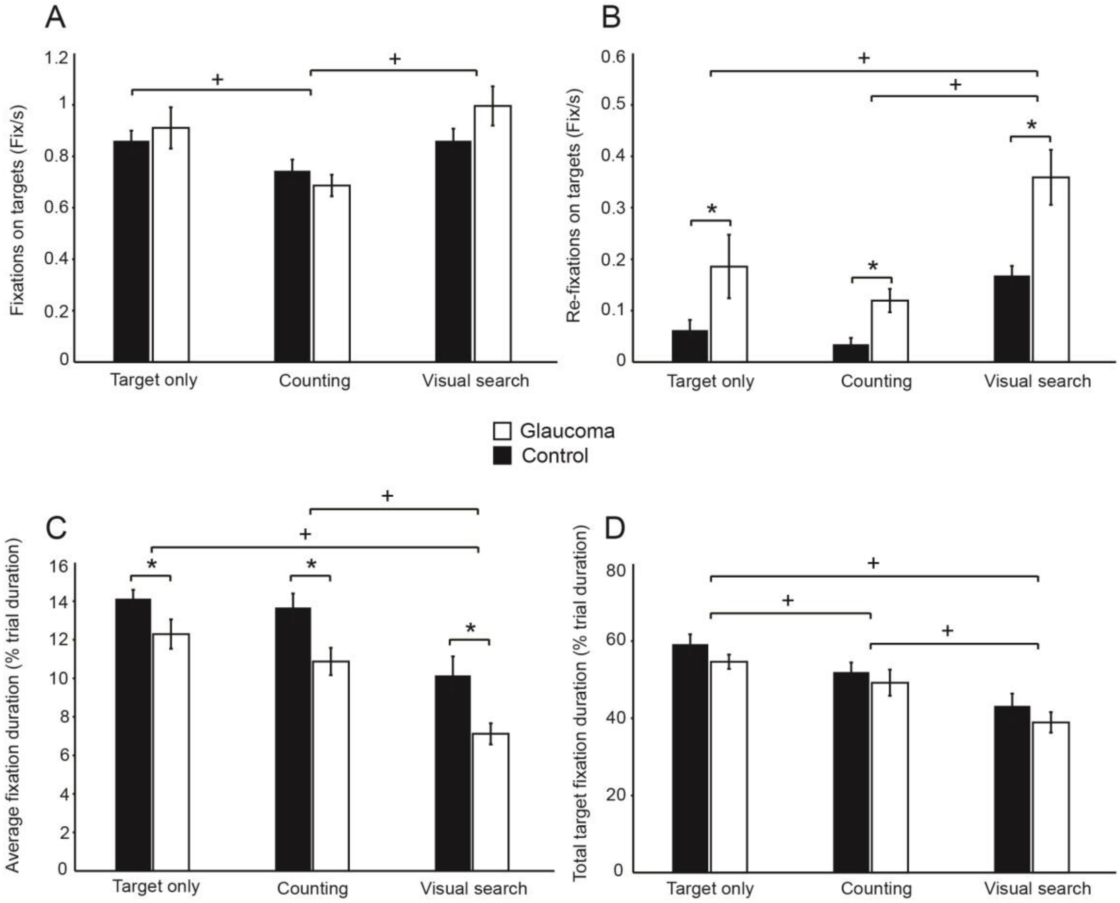


Fig 2.3: Mean (+/- SE) fixations to targets (A) and re-fixations to targets (B) are shown, as well as average fixation duration (C) and total target fixation durations to targets (D). Group (*) and condition (+) main effects are depicted for all four measures.

Saccade, foot-event timing:

The timing relationship between stepping events and saccades to/from targets was different between groups, and across conditions (Fig 2.4). There was a significant main effect of group ($F_{1,26} = 8.59$, $p = 0.007$) and condition ($F_{2,52} = 25.84$, $p < 0.0001$) for saccade – heel contact latency (Fig 2.4a). Further tests showed a more negative value for the glaucoma group, and more negative values for the counting and visual search conditions compared to target only, meaning that a subject looked away from a target sooner compared heel contact. A similar pattern showing main effects of group ($F_{1,26} = 7.70$, $p = 0.01$) and condition ($F_{2,51} = 25.81$, $p < 0.0001$) were seen for saccade – toe-off latency, with post hoc tests showing more negative values for the glaucoma group, and the counting and visual search conditions, meaning they looked to a target sooner compared to toe-off to that target. (2.4b).

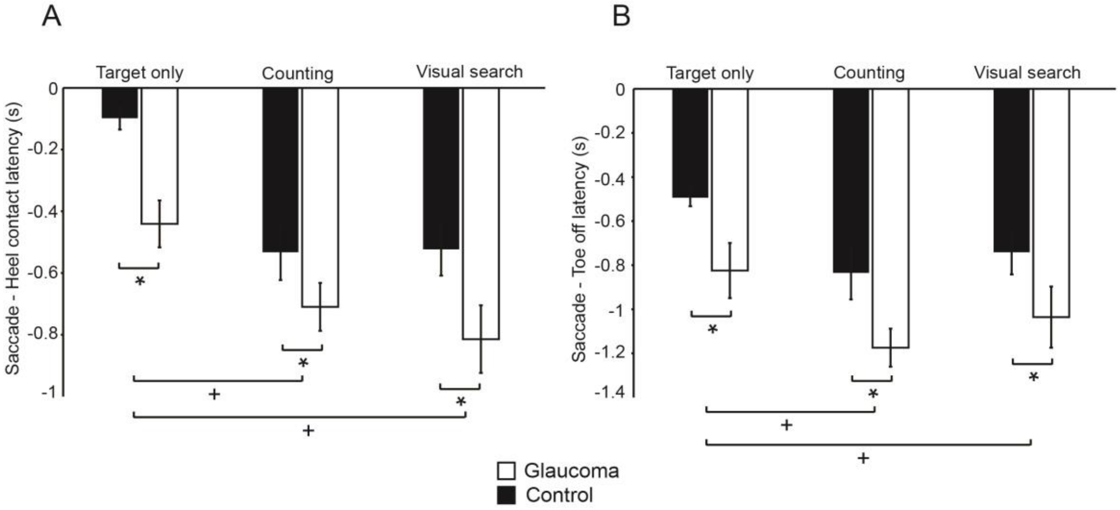


Fig 2.4: Mean (+/-SE) saccade heel-contact latency time (A) and saccade toe-off latency time (B) are shown comparing both groups and all three conditions. A more negative number in both cases indicates saccades were made sooner from or to the impending target, respectively. Group (*) and condition (+) main effects are shown.

2.3.2. Association with visual field loss:

Mobility:

Relationships were evident between our mobility measures and the severity of visual field loss for the glaucoma group. Simple linear regressions were used to show correlations between foot placement error and MD for each of the conditions separately (Fig 2.5a). Analysis revealed a significant correlation between these measures for the counting ($\beta = 4.56$, $p = 0.009$, $R^2 = 0.444$) and the visual search conditions ($\beta = 4.10$, $p = 0.006$, $R^2 = 0.485$), and a strong trend for the target only condition ($p = 0.06$). Here, foot placement error increased as visual field loss increased (Fig 2.5a). Strong associations were also found between foot placement variability and MD for the target only ($\beta = 2.70$, $p = 0.015$, $R^2 = 0.402$), counting ($\beta = 2.89$, $p = 0.001$, $R^2 = 0.642$), and visual search conditions ($\beta = 3.93$, $p = 0.0003$, $R^2 = 0.673$). In all instances, foot placement variability increased with increasing visual field loss (Fig 2.5b). No differences between slopes across groups were detected for either measure ($p > 0.05$).

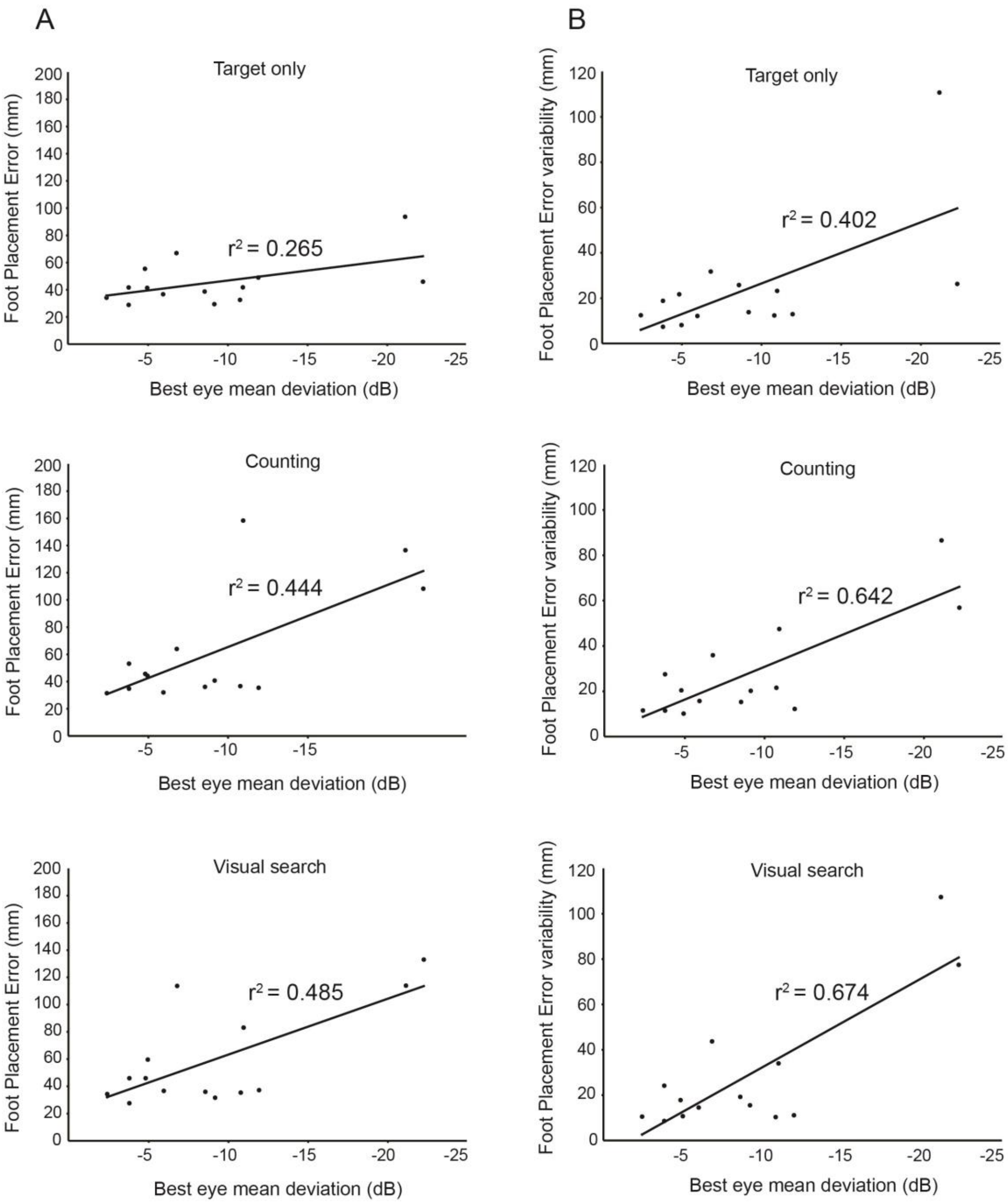


Fig 2.5: Results of the regression analysis depicting relationships between visual field loss and (A) foot placement error and (B) foot placement variability across the different conditions. Slopes were significantly different from zero, with the exception of the target only condition in panel A.

Gaze Behaviour:

Simple linear regressions showed no significant associations between MD (representing visual field loss) and number of fixations on targets, target re-fixations, average fixation duration, and total fixation duration. However a strong trend was observed for total fixation duration and visual field loss in the target only condition ($\beta = -0.01$, $p = 0.056$, $R^2 = 0.294$), where increasing visual field loss associated with decreasing total fixation duration.

Saccade, foot – event timing:

Simple linear regression for saccade heel-contact latency and saccade toe-off latency, respectively, were run separately for each condition. A correlation between saccade – heel contact latency was seen during the target only condition ($\beta = -0.03$, $p = 0.048$, $R^2 = 0.289$). Earlier saccades away from a target with respect to heel contact with that target were associated with visual field severity in this condition.

2.3.3. Association between mobility and gaze measures:

Simple linear regression for all groups and conditions were run comparing all four gaze and both saccade – foot event measures to the two mobility measures. No significant associations were found between any of the measures, but strong trends approaching significance were found between saccade – heel contact latency and foot placement error for the target only ($\beta = 28.54$, $p = 0.071$, $R^2 = 0.247$) and visual search conditions ($\beta = 41.53$, $p = 0.077$, $R^2 = 0.238$) for those with glaucoma. Here more negative saccade – heel contact latency values were associated with increased foot placement error.

2.3.4. Dual task cost:

Dual task performance:

Dual task cost ratio was significantly different from 1 (a value of 1 meaning no cost/decrease in performance) for the counting task as indicated by a one-sample t-test for glaucoma ($T = -9.45$, $p < 0.0001$) and control groups ($T = - 5.17$, $p < 0.0001$), who both show a decline in performance. A paired t-test showed that the glaucoma group had significantly greater costs compared to controls ($T = -3.28$, $p = 0.002$), as their cost ratio (dual task counting performance divided by baseline counting performance) was smaller. In addition, costs were significantly less than 1 for the visual search task for both glaucoma (T = -1.90, p = 0.04) and control groups (T = -2.70, p = 0.009). No differences in visual search cost between the groups were found.

Visual search task gaze behaviour to shapes:

One-way ANOVA comparing the four normalized gaze behaviour measures across groups with respect to the shapes revealed a significant main effect of group for the number of shape re-fixations. Those with glaucoma made more re-fixations to the shapes ($F_{1,26} = 6.22$, p = 0.019). However, no evidence for differences between groups was found for number of fixations to shapes, average fixation duration to shapes, or total fixation duration to shapes.

2.4. Discussion:

In everyday walking the multifaceted relationship between sensory input and motor control that allows us to step to specific locations is compromised with visual impairment. When the ground terrain is uneven, such as on a bumpy sidewalk, vision plays a crucial role in identifying footfall areas for safe navigation (Marigold 2008; Marigold & Patla, 2007). The aim of this study was to investigate the ability of persons with glaucoma to accurately place their feet during walking, and to identify the gaze behaviours they use to do so. We found that both foot placement error and variability increased for people with glaucoma compared to controls. Also, people with glaucoma looked to the same target more frequently, and for a shorter average duration. The timing relationship between saccades to and from targets and stepping events also differed for people with glaucoma, such that they looked more to future targets rather than the one they were stepping on.

Walking is seldom done without the presence of visual distractions, or other things to think about. To investigate the effects of simultaneously walking and dual tasking, we had subjects either count backward or search the walkway for shapes as they stepped. The findings indicate that dual tasking while walking decreased mobility performance for both groups. In addition, having to visually search the environment leads to altered gaze behaviour toward the stepping targets. Dual tasking also affected the timing relationship between saccades to targets and stepping, in a way that was detrimental to mobility.

2.4.1. Effects of glaucoma on mobility during precision walking

People with glaucoma were found to have greater foot placement error and variability when stepping to targets compared to healthy older adults. This reduced control of foot placement is evident in the general older population who have more difficulty with walking than their younger counterparts, which can lead to injurious falls (Chapman & Hollands 2006, 2007; Chapman et al., 2012; Grabiner et al., 2001; Menz et al., 2003). In fact, older adults that are at a higher risk for falling have even less stepping accuracy, similar to those with glaucoma in our study (Chapman & Hollands, 2006). Interestingly, control of foot placement in a similar precision walking task is reduced in subjects with AMD (Alexander et al, 2014), but only in poor lighting conditions. This suggests a profound importance of both peripheral and central vision for precise control of foot placement. Foot placement error also increased in a linear fashion with increasing visual field loss, which was not found in subjects with AMD (Alexander et al., 2014). The decreased mobility performance seen in people with glaucoma is therefore most likely related to the fact that they cannot see as much of their environment at a given time, and are not able to compensate for their visual field loss in a way that preserves mobility. The severity of mobility loss in this task is related to the degree of visual field loss a person has. People with greater vision loss are predictably more likely to miss steps that could lead to falls. Overall, our findings provide experimental evidence to support the notion that people with glaucoma have mobility problems in tasks other than obstacle navigation (Friedman et al., 2007).

2.4.2. Effects of glaucoma on gaze behaviour during precision walking

Stepping toward or avoiding certain features of the environment requires adequate and timely visual input. Peripheral vision, particularly from the lower visual field, lets us monitor foot position and target/obstacle characteristics without looking at them directly (Marigold et al., 2007; Marigold, 2008). Interestingly, subjects with glaucoma spent less time looking at the stepping targets, indicating that they looked to the ground around the targets more than control subjects. This might suggest that people with glaucoma direct their gaze to features of the ground that they cannot monitor using peripheral vision. This finding is similar to those of Turano and colleagues (2001), where people with visual field loss due to RP looked to areas of a hallway that were not relevant to the walking task. In contrast, little differences in fixations to AOIs were found for people with glaucoma when walking across a street, yet this task does not require precise control of foot placement (Geruschat et al., 2006).

Our findings also suggest that when stepping to targets people with glaucoma are more likely to look back to the same target repeatedly, and as a result spend less time looking at a target, per fixation. The higher re-fixation behaviour can be interpreted as a strategy to obtain more information on particular footfall targets during walking, since they cannot be constantly monitored using peripheral vision. It follows that this may improve the visuo-spatial representation of their walking environment. Unfortunately, mobility performance is not spared in the presence of these strategies, likely due to the timing relationship between when a target is fixated, and when a step is made towards it.

Our findings indicate that people with glaucoma are more likely to look away from footfall locations of the current step and toward future footfall locations sooner during precision walking. Under normal conditions, healthy people initiate a saccade toward a target and away from a target almost simultaneously with when they initiate a step toward the target or make heel contact with the target, respectively (Hollands et al., 1995; Hollands & Marple-Horvat, 2001; Patla & Vickers, 1997, 2003). This timing is crucial for obtaining information about the targets and the foot so that foot trajectory can be chosen and monitored appropriately. Similar changes to this timing relationship that are seen in our glaucoma subjects has been seen in older adults who are at a higher risk for falls (Chapman & Hollands, 2007). These people were also less accurate and more variable with their foot placement, similar to the group differences seen in our study. This behaviour might suggest that older adults at a higher risk for falls are more worried about future steps at the expense of monitoring their foot placement (Chapman & Hollands, 2007). Thus, the similar behaviour found in our study likely indicates that people with glaucoma are concerned with finding future footfall targets sooner, at the expense of monitoring foot placement during a step. In addition, there is a dose-response relationship, whereby greater visual field loss relates to more abnormal saccade – stepping timing. This in turn may contribute to the decrease in precise control of foot placement. The implications of these findings are relevant to people with early stage glaucoma who will likely progressively lose their vision and adopt this ill-advised saccade step timing.

2.4.3. Impacts of dual tasking during precision walking on gaze and mobility

The results of this study demonstrate increased foot placement variability when dual tasking to a similar degree for both the cognitive and visual search tasks, but greater foot placement error during the visual search compared to counting. In both of these conditions, foot placement error and variability were worse for people with glaucoma. Therefore, similar to other studies, our findings show that healthy adults experience poorer stepping performance when dual tasking, but we are the first to show a larger effect in people with glaucoma (Beurskens & Bock, 2013; Bock & Beurskens, 2011; Simoni et al., 2013; Telonio et al., 2014). Negative effects of dual tasking on gait have been shown in older adults during obstacle avoidance tasks as well, and should be investigated for people with glaucoma (Hegeman et al., 2012). The demands that a secondary task places on working memory and attention are enough to disrupt gait, and show effects on gaze behaviour as well.

As expected, gaze behaviour differed during the visual search task compared to the counting task. The nature of the task design was such that vision was distracted from the targets, toward other AOIs (i.e., the shapes). This is structural interference that was purposely imposed to force changes in gaze behaviour that mimic natural walking to see how that would impact mobility performance. While doing the visual search dual task, both groups looked back to the same target more frequently, but spent less time overall looking at the targets. Also, saccade step timing was disrupted such that when performing either dual task, footfall location identification was prioritized for targets that were further ahead. All of these effects were more pronounced for people with glaucoma. The effects on dual task performance indicate a cost to both the cognitive and visual search secondary tasks, which are greater for people with glaucoma. The outcomes of the present study are consistent with those that show older adults performing dual tasks that divide visual attention while walking, have poorer performance on the secondary task (Bock, 2008). We also show similar effects under cognitive dual tasks. These paradigms are critical to investigate because the ability to count backward while walking is strongly associated with falls risk in older adults (Beauchet et al., 2007). The data from this study support this notion, where people with glaucoma, who are at a higher risk for falls, also have poorer counting performance during walking compared to healthy older adults. Also, disrupted walking performance and gaze patterns during more complex walking tasks while dual tasking has been shown in people with Parkinson's disease (PD) (Galna et al., 2012). In this study, people with PD had reduced saccade frequency compared to controls when preparing for a turn during a cognitive dual task. Similarly, in our study, people with glaucoma made less fixations to targets during the cognitive dual task and spent less total time fixating the targets. This was not apparent when vision was distracted during the visual search dual task, which reflects the importance of recognizing the distinct effects different dual tasks have on gaze behaviour, and how they can impact walking.

2.4.4. Conclusion

This was the first study to explore links between visual field loss, mobility, gaze behaviour and dual tasking. The data indicated that older adults with glaucoma had reduced control of foot placement on targets during a precision walking task, and that this effect is larger as visual impairment increases. People with glaucoma were more likely to re-fixate on the same target, and to spend more total time looking to the ground around targets. Also, the pattern of gaze behaviour varied such that the timing relationship between stepping and looking to targets was altered with glaucoma in a way that may be detrimental to mobility. This behaviour is indicative of a more cautious strategy that prioritizes identifying future footfall locations, but neglects monitoring foot trajectory. These mobility effects were exacerbated by multitasking while walking, and gaze behaviour varied depending on the nature of the dual task. Future research should aim to identify whether modifying gaze behaviours can improve mobility, or vice versa, with and without multitasking, and investigate similar mobility and gaze parameters in other visually guided walking tasks, like obstacle crossing or stair climbing.

Chapter 3. Mobility and gaze behaviour during obstacle navigation in people with glaucoma

3.1. Introduction

During locomotion, vision of our surroundings allows us to monitor where we want to go, and how to get there. Often, there are obstacles in our way, such as people in a crowd, and we rely on head and eye movements called gaze behaviour to obtain the information necessary to avoid them (Patla et al., 2007). When disease affects the eyes, and vision is diminished, executing everyday tasks becomes difficult. Older adults are particularly vulnerable to mobility impairments and falls as a result of age-related eye diseases (Friedman et al., 2007; Popescu et al., 2011, 2012; Swenor et al., 2015; Tanabe et al., 2012).

Glaucoma affects over 60 million people worldwide, leading to irreversible loss of peripheral vision (Tham et al., 2014; Weinreb et al., 2014). Mobility issues are among the most common complaints in people with vision loss from glaucoma, and as a result, they are less likely to leave their homes (Popescu et al, 2011; Ramulu, 2014; Swenor et al., 2015). In fact, those with glaucoma often have difficulty with tasks like shopping, climbing stairs, and navigating around obstacles (Friedman et al., 2007; Hochberg et al., 2012; Viswanathan et al., 1999). When negotiating an obstacle course, people with visual field loss in both eyes due to glaucoma walked more slowly and were more likely to bump into obstacles, which can then lead to falls (Friedman et al., 2007).

For people with healthy vision, obstacles are successfully navigated using the combined input of central and peripheral vision. Central vision is used primarily to obtain information on features that make up the border of a path towards a goal, and on the goal itself (Patla et al., 2007). Normally, healthy adults do not have to fixate every obstacle in their path, but always look to the end-goal for some amount of time in order to align their body trajectory with it (Franchak & Adolph, 2010; Hollands et al., 2002). In situations where moving obstacles must be avoided, such as pedestrians on a sidewalk, gaze directs central vision toward those that are most likely to collide with the subject (Jovancevic-Misic & Hayhoe, 2009). On the other hand, virtual navigation experiments indicate that peripheral vision is used to maintain a representation of the surrounds that is constantly updated (Turano et al., 2005).

For people with glaucoma, peripheral vision can be compromised, and therefore normal gaze behaviour may not be adequate to avoid collisions. Distinct differences in gaze behaviour have been seen for people with glaucoma in several tasks. For instance, people with visual field loss similar to that seen in glaucoma were more likely to look to unimportant areas (the walls and floor) when walking to a door at the end of an empty hall (Turano et al., 2001). In addition, when viewing a virtual driving scene, more saccades are made overall (to look to different areas more frequently), but hazards are still missed more often (Crabb et al., 2010). These behaviours suggest that people with visual field loss are trying to compensate for their lack of peripheral vision by looking to more areas more frequently. However, this adapted gaze behaviour does not eliminate the times where important features are missed and may not be enough to reduce the number of times dangerous collisions with obstacles are made. The link between gaze behaviour and negotiating obstacles while walking is not clear, and may explain the frequent collisions reported in this population.

Walking in natural environments exposes us to many distractions that can demand attention. Performing various types of dual tasks while walking negatively impacts mobility in older adults, especially tasks that require visual attention (Bock & Beurskens, 2011). To understand how glaucoma impacts mobility during walking, it is important to investigate the mobility and gaze behaviour of people with reduced visual fields in situations where they also have to perform a cognitively and/or visually demanding secondary task.

The aim of this study was to determine how gaze behaviour and mobility are affected by glaucoma during obstacle navigation under multitasking conditions. This experiment achieved these aims by having older adults with and without glaucoma walk through a series of vertical poles toward an end-gate with and without dual-tasking. Subjects walked around obstacles in three conditions: navigating obstacles only, navigating while counting backwards by serial threes, and navigating while identifying the sequence of shapes around the walkway. We hypothesized that mobility performance would be reduced for people with glaucoma such that more collisions with obstacles would occur and poorer path choices would be taken. Also, we hypothesised that subjects with glaucoma would be more likely to look closer to their feet as they walk, and to look at the poles more frequently. In addition, we hypothesized that older adults with and without glaucoma would collide with more obstacles and would look closer to their feet during dual task conditions.

3.2. Methods

3.2.1. Subjects

28 older adults were recruited for this study (all participated in the experiment of chapter 2 as well): 13 had glaucoma (9 men, 4 women; age, 73.7 ± 5.6 yrs), and 15 were healthy-eyed controls (10 men, 5 women; age, 70.1 ± 5.5 yrs). There were no significant differences in age (p=0.054). Subjects were selected using convenience sampling, with glaucoma subjects recruited through a collaborating ophthalmologist, and control subjects recruited from community centers and an eye clinic.

Participants were included if they were 60 years of age or older and were able to understand instructions in English. Also, visual field requirements were such that people with glaucoma needed to have a better eye MD score worse than -2dB, and control subjects needed a worse eye MD score better than -2dB. Subjects were excluded if they presented with any other uncorrected significant eye condition (cataracts, AMD), osteoporosis, a Mini-Mental State Exam (MMSE) score less than 25 (Folstein et al., 1975), or a neurological or musculoskeletal disorder that affected their balance and/or walking. The Office of Research Ethics at Simon Fraser University approved the study, and all participants gave written consent prior to performing the experiments.

3.2.2. Ancillary measures of vision and mobility

Eye health and visual function were assessed at the eye clinic, or at the Sensorimotor Neuroscience Laboratory at Simon Fraser University. Visual field scores for glaucoma subjects were obtained at the ophthalmologist's office using a Humphrey systems visual field analyzer (model HFA-II 750; Carl Zeiss Meditec, Inc., Dublin, CA) via the SITA-Fast central 30-2 threshold test procedure (size III Goldmann white target and background luminance of 10.03 cd/m^2). For control subjects a Humphrey systems visual field analyzer (model REF, 710 series; Carl Zeiss Meditec, Inc., Dublin, CA) was used at the lab. This analyzer used frequency doubling technology perimetry, with 10^o by 10^o targets of varying contrasts made up of black and white vertical sine wave grating of low spatial frequency (0.25 c/deg) undergoing counter-phase flickering at 25Hz. Both forms of visual field analyses are effective for monitoring vision loss with glaucoma (Nouri-Mahdavi, 2014). Binocular visual acuity, contrast sensitivity, and stereoacuity were obtained using standardized Snellen line examination charts on a SIFIMAV Vision Tester (Mav-III; SIFI, Italy), using the Melbourne Edge Test (MET) at a distance of 40 cm (Verbaken & Johnston, 1986), and using a RANDOT stereopsis test (Stereo Optical Company, USA), respectively, as described in Chapter 2. Three sub-tests on useful field of view software were used to assess central processing speed, divided visual attention ability, and selective visual attention at a distance of ~50 cm from a computer monitor (UFOV, Version 7.0.2, FL, USA). To determine central vision processing speed, subjects identified the presence of either a white car or truck that appeared briefly in the middle of the screen. The software decreased the length of stimulus presentation until a subject is able to correctly identify the item 75% of the time. Divided visual attention ability of the subject was assessed using the same central stimulus identification in the center of the computer screen. In this case, subjects also had to identify the location of a simultaneously appearing car in the periphery at one of eight locations 15 cm radially from the central stimulus. A similar method where 75% correct responses were given determined the timing threshold for this test. Subject's selective visual attention was assessed using a similar method, except that 47 triangles were also present on the screen to distract the observer from the location of the radially located car. Scores for all tests are reported in ms, indicating the stimulus duration a subject requires to successfully perform each test 75% of the time.

To evaluate general mobility function, subjects performed the timed up-and-go test (TUG), which required them to stand up from a chair, walk 3 m, turn, walk back, and sit back down (Podsiadlo & Richardson, 1991). Subject characteristics including visual, mobility and cognitive results are outlined in Table 3.1.

Table 3.1: Subject visual scores of glaucoma and control groups

Measure	Glaucoma Group	Control Group	P-value
Best Eye MD (dB)	-9.6 ± 5.9	0.8 ± 1.7	<0.001
Worse Eye MD (dB)	-18.1 ± 7.4	0.2 ± 1.9	<0.001
Binocular Contrast Sensitivity – OU (dB	16.5 ± 2.1	19.7 ± 1.1	<0.001
Stereopsis – OU (s^{-1} arc)	190.8 ± 118.1	60.7 ± 56.0	0.001
Visual Acuity – OU (log units)	0.1 ± 0.09	0.02 ± 0.1	0.01
Visual Processing Speed – OU (UFOV 1 Score)	71.2 ± 103.5	13.9 ± 1.6	0.04
Divided Visual Attention – OU (UFOV 2 Score)	228.3 ± 190.1	99.9 ± 88.7	0.02
Selective Visual Attention – OU (UFOV 3 Score)	325.6 ± 144.6	186.7 ± 109.3	0.01
MMSE (Score/30)	28.8 ± 0.9	29.5 ± 0.6	0.02
TUG (s)	9.8 ± 2.1	9.0 ± 0.8	0.1

Note: Abbreviations: MMSE = Mini mental state exam; OU = Oculus uterque (both eyes); TUG = timed up & go; MD = mean deviation.

3.2.3. Procedure:

The obstacle navigation task required subjects to walk around 4 black vertical poles (height, 165cm, diameter, 3.5cm), toward and through an “end gate” that consisted of two blue vertical poles (height, 25cm, diameter, 6 cm) (Fig 3.1a). The poles were arranged along a 4.5 m long x 1.25 m wide walkway. Obstacle and end gate positions were varied trial-to-trial, such that one of four pre-determined arrangements would occur in a random order. Poles were always spaced 60cm from each other in the anterior-posterior (AP) direction, but varied in the medial-lateral (ML) direction. Each configuration was designed such that there was a clear path choice allowing the subject to get from the start position to the end gate. To ensure that subjects required vision to navigate, the positions of the obstacles were varied each trial. Subjects were instructed to walk at a self-selected speed, and to navigate the course so that they reached the end gate by taking the simplest route they saw and without any part of their body going outside the lateral walkway borders or contacting the poles. Vision of the walkway was blocked prior to each trial with a wooden board. Subjects were instructed to start walking immediately once the "go" signal was given. During the experiment, all subjects wore their habitual vision correcting lenses.

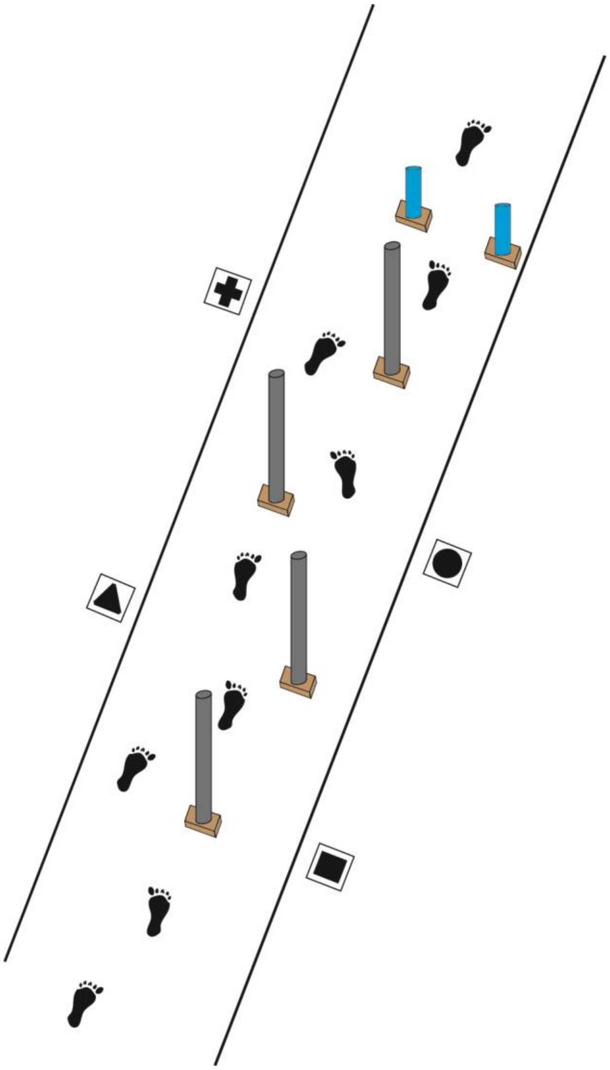


Figure 3.1: Experimental set-up for the obstacle navigation task with visual search shapes shown (only present during visual search condition).

Subjects performed the obstacle navigation task under three conditions, each presented in blocks of 12 trials and fully randomized for a total of 36 trials. In the "obstacle only" condition, subjects were simply required to perform the obstacle navigation task. This condition served as a baseline where all focus was directed toward the walking task. In the "counting" condition, subjects were instructed to count backwards by serial threes from a random two-digit number between 50 and 100. Baseline performance was measured in three trials prior to the walking task while the subject sat and listed as many correct numbers as they could in ten seconds. In the dual task condition, where subjects walked through the poles and counted backwards by threes, the additional instructions were to always continue walking, and to say as many numbers as possible until reaching the end gate. A researcher listening to the participant's sequential correct responses measured counting score. Response values for baseline and dual task conditions were normalized to number of correct responses per second. In the "visual search" condition, subjects had to observe and remember the sequence of four black shapes (13 cm length or diameter) printed on white tiles (20 cm x 15 cm) laid out on the sides of the walkway. The position on the floor that the four shapes (cross, triangle, circle, square) could appear was always the same. However, the specific shape at these locations varied according to four randomly selected sequences each trial (Fig 3.1a). At the end of the walking portion of each trial, subjects stopped facing away from the walkway and were asked to recall the location of one of the shapes, selected at random. Visual search score was measured as the correct number of responses/12 trials. To establish a baseline of performance without a dual task, subjects stood still at the start of the walkway and were given four seconds (the average duration pilot subjects could see the shapes during walking) to remember the sequence of the shapes. Their vision was then blocked, and they were asked to recall the position of one randomly selected shape. This was repeated 12 times, and their baseline score was also recorded as above.

3.2.4. Data and statistical analysis

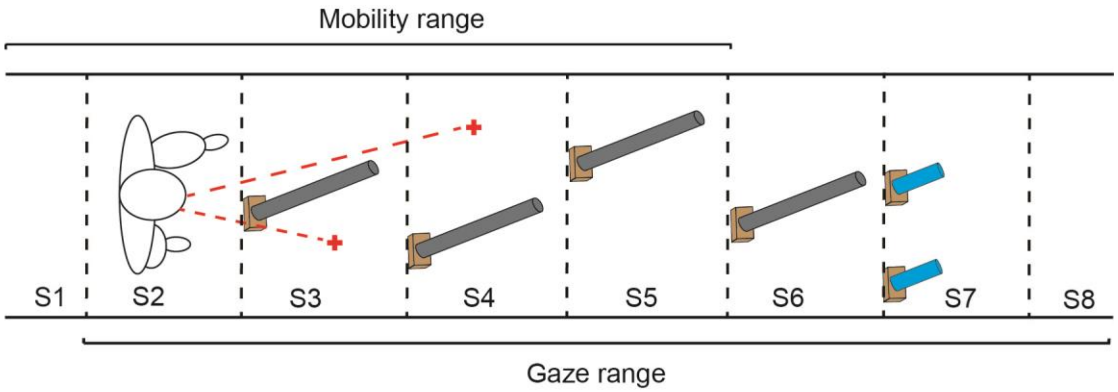
Kinematic data were recorded at 120 Hz using Optotrak Certus motion-capture markers located on the head, chest, and shoulder, and bilaterally on the foot at the toe, mid-foot, and heel (Northern Digital, Inc., Waterloo, Canada). Kinematic data were filtered using a Butterworth low pass filter at 6 Hz in MATLAB, and then analyzed using custom-written LabVIEW (National Instruments, Austin, TX) programs.

Four measures were used to evaluate mobility performance, including gait speed, path choice, number of obstacle collisions, and chest trajectory variation. Gait speed was determined as the time it took the chest marker to pass from the first to the last obstacle, divided by AP distance. Path choice was determined by recording the number of trials per condition where a subject did not take the easiest path (defined as the path with the largest average ML aperture between obstacles or the walkway border, thereby requiring the least amount of trunk rotation to pass without contacting obstacles). The number of collisions with obstacles per trial was evaluated by recording the occurrences where any part of a subject's body contacted an obstacle or end-gate, and was verified by a second researcher who was present during testing. Lastly, chest trajectory variation was measured during obstacle navigation, and was calculated as the root-mean-square error of the chest marker change in trajectory (yaw) in degrees in the transverse plane over the course of each trial.

Gaze data, also recorded at 120 Hz, were obtained using an H6 high-speed head-mounted eye tracking system from Applied Science Laboratories (ASL) (Bellerica, MA, USA). The software produces a gaze location shown by crosshairs on a scene video from a camera located on the subject's forehead recorded at 30Hz. In addition, location of gaze in 2-dimensional coordinates with respect to the size of the scene image was obtained at 120 Hz. Gaze data were filtered using a Butterworth low pass filter at 6 Hz in a MATLAB program. Eye rotation was evaluated using gaze position on the head-mounted camera image, differentiated to velocity, and filtered using a custom MATLAB program. Saccade start and end times were identified using a custom LabView program, where eye rotation velocity surpasses and returns below 100 degrees/s (Chapman & Hollands, 2006). The location of gaze with respect to each AOI was determined using the position of the crosshair on the 30Hz scene video from the perspective of the subject. Fixations were defined as instances where gaze location was stable on an AOI for > 67 ms (Turano et al., 2001). AOI's included ground segments, obstacles, end gates, and shapes when applicable. Fixation duration was defined as the time when a saccade away from an AOI was started, minus the end time of the saccade toward that AOI. Fixation durations included times where saccades were made within the same AOI. Fixation and saccade times were therefore identified and quantified using data recorded at 120 Hz, with the AOIs classified using the 30 Hz video.

Gaze behaviour was assessed in all condition using several measures, all averaged across trials within a condition, and with eight of them normalized to trial duration length. These included the number of fixations on obstacles, re-fixations on obstacles, average fixation duration on obstacle, and the same four but with regards to the end gate.

We also calculated a “gaze distance” measure, which represented how far ahead a subject looked with respect to their position on the obstacle path on average over the course of each trial. This was obtained by dividing the walkway into 8 segments of equal length (except S1, which represented the time before toe-off of the first step, and a longer last segment (S8) past the end of the walkway) (Fig 3.2). First we identified which segments were fixated when the subject’s torso was located in a given segment, or before toe-off (in the case of S1). Subject’s passage from one segment to the next was identified using chest crossing obstacle time, or toe-off of the first step (S1). The kinematic measures for chest crossing time and toe-off were obtained using a custom LabVIEW program. The duration a subject spent in each segment (T) was evaluated for segments S1 to S5 (mobility range), and the percentage of time spent fixating each segment ahead of the subject with respect to the total time a subject fixated the obstacle course was determined separately for each mobility segment ($\%F_{TSx}$). When a subject walked in S6 through S8, gaze was often directed to areas irrelevant to the task (walls, desks) and could not be quantified accurately. Therefore, the analysis included only when subjects walked from S1 to S5 and looked to segments S2 to S8 (gaze range). This percent time fixating in one segment while walking in a given segment was averaged across trials within a given condition ($avg\%F_{TSx}$). In this way, for every segment a subject walked in, the total percent time looking to segments ahead in the gaze range for a given condition was 100%. To calculate a gaze distance for each mobility segment, a value of zero plus the number of segments they are looking ahead was multiplied by the average percent time looking at that given gaze segment per condition, and divided by 100%. After the gaze distance was calculated for S1 through S5, the values were normalized by multiplying each of them by the fraction of time the subject spent in that segment (averaged over all trials in a condition), over the total time the subject walked from S1 to S5. Although it only varied slightly, this was done to ensure that if a subject walked slower or faster in a given segment (spent more or less time in each), the weight that segment carried in the overall gaze distance measure was taken into consideration. Then, the sum of the weighted gaze distances for each of segments S1 to S5 was calculated to obtain only one gaze distance value for each condition. For the purpose of the gaze distance measure, any pole that was located within a given ground segment was considered part of that segment (Fig 3.2).



$$\text{Gaze distance when in S2} = \{(\sum_{i=3}^{8} (\text{avg}\%F_{TSi} \times S_D))/100\} \times (T_{S2} / \sum_{i=1}^{5} T_{Si})$$

$$\text{where} \quad \%F_{TSx} = (F_{TSx} / F_{TST}) \times 100$$

$$\text{and} \quad \text{avg}\%F_{TSx} = \sum_{i=1}^{n} (\%F_{TSx})_i / n$$

Figure 3.2: Gaze distance measure diagram and calculations. In this figure the equations used to calculate gaze distance are shown for the duration of time the subject is in S2 (gaze range S3-S8). In reality, subjects could look to many segments while walking in each one, but fixation times are summed across all gaze segments to always total 100%. The mobility range (S1-S5) and gaze range (S2-S8) are shown with the poles that are included in those segments. The equation used to calculate weighted gaze distance for only when the subject is in S2 is shown. For the total gaze distance over an entire trial, those five values are summed across S1-S5.

Definitions: F_{TSx} = time spent fixating segment x, F_{TST} = the total time segments were fixated while in a given segment, n = the number of trials used in gaze distance calculation per condition, $\%F_{TSx}$ = percent fixation time to a given segment of total fixation time while in one mobility segment, avg% F_{TSx} = average percent fixation time to a given segment across trials, T = average time spent walking in a segment, S_D = zero plus the number of segments ahead each fixation is located with respect to the segment the subject is in.

Also, two more measures, the time latency between a saccade was made to and from an obstacle relative to when the subject's chest crossed it was determined.

Subject's change in performance from baseline to dual tasking for the counting and visual search measures was evaluated as the dual task "cost" (count/visual search performance during dual task divided by count/visual search performance baseline value). Gaze behaviour with respect to the shapes during the visual search task was evaluated using four measures normalized to trial length: number of fixations on shapes, re-fixations on shapes, average fixation duration on shapes, and percent fixation time on shapes per trial.

Statistical analyses were performed using JMP 11 (Cary, USA) software with an α-level set at 0.05. Group and condition differences in mobility and gaze measures were investigated using two-factor (Group x Condition) ANOVAs. Tukey's post hoc tests were used to identify the nature of differences between levels when ANOVAs revealed significant results. The relationship between gaze/mobility measures and the severity of visual field loss, and between gaze and mobility measures was determined using linear regression analysis for the glaucoma group, and each walking condition separately. The differences between slopes were then tested using a one-way ANOVA, if appropriate. To investigate if dual task costs were present, they were compared to a value of 1 (no cost) using a one-sample t-test, and differences in dual task costs between groups were also investigated using paired t-tests. Finally, one-way ANOVAs were used to identify group differences in gaze behaviour measures related to the shapes during the visual search condition.

3.3. Results

3.3.1. Mobility and gaze behaviour differences between groups and conditions

Mobility:

Several features of mobility that were investigated gave insight into the contrasting obstacle navigation capacities of people with and without glaucoma, and the effects of dual tasking. A significant interaction between groups and conditions ($F_{2,52} = 5.42$, $p = 0.007$) was found for number of obstacle collisions. Post-hoc tests showed that the control group had lower collisions in all conditions compared to the glaucoma group, with the exception of the obstacle only task (Fig 3.3a). Also, collisions were greater in the visual search condition compared to the obstacle only condition for those with glaucoma. Group ($F_{1,26} = 6.99$, $p = 0.014$) and condition ($F_{2,52} = 24.69$, $p < 0.0001$) main effects were seen for gait speed, such that subjects with glaucoma walked slower, and walking was slowest when counting, and fastest during the obstacle only task (Fig 3.3b). Chest trajectory variation differed between groups ($F_{1,26} = 4.82$, $p = 0.037$), where those with glaucoma showed greater trajectory changes. This differed between conditions ($F_{2,52} = 18.58$, $p < 0.0001$) such that it was higher when counting compared to the other conditions (Fig 3.3c). Differences were not found for path choice between groups or conditions. These findings indicate poorer obstacle navigation for those with glaucoma, who were more likely to collide with obstacles, walk slower, and alter their body trajectory. Dual tasking increased these effects for both the glaucoma and control group.

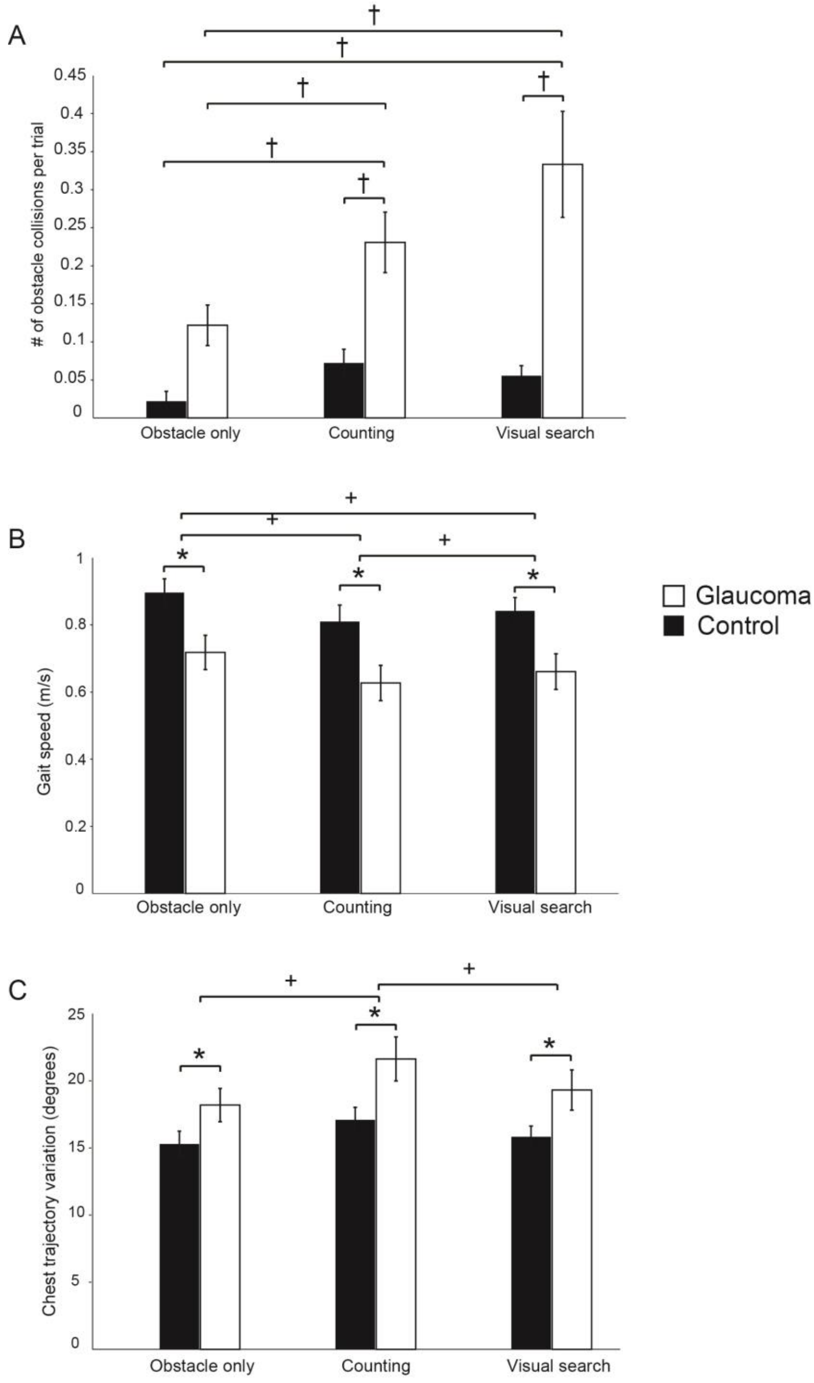


Figure 3.3: Mean (+/-SE) obstacle collisions (A), gait speed (B) and chest trajectory variation (C) are shown comparing groups and conditions. Group (*) and condition (+) main effects, and significant differences with interactions (†) for all measures are shown.

Gaze Behaviour:

Features of visual sampling behaviour during obstacle navigation for people with glaucoma were compared to healthy age-matched controls. Gaze behaviour differed between the groups and conditions for several measures related to obstacle fixations. For number of obstacle fixations, an ANOVA revealed a main effect of group ($F_{1,26} = 7.70$, $p = 0.01$) and condition ($F_{2,52} = 12.18$, $p < 0.0001$) (Fig 3.4a). Further analysis showed that people with glaucoma fixated on obstacles more and that fewer fixations were made to obstacles when counting compared to the visual search and obstacle only conditions. In addition, the glaucoma group re-fixated on obstacle to a greater extent than controls, as evident from a group main effect ($F_{1,26} = 4.58$, $p = 0.042$; Fig. 3.4b). Also, the average duration of fixations to an obstacle differed between conditions ($F_{2,52} =3.31$, $p = 0.044$), such that shorter durations were evident during the visual search condition compared to the counting condition (Fig 3.4c). There was also a main effect of group ($F_{1,26} = 4.60$, $p = 0.042$) when analyzing the total time spent looking at obstacles in a given trial (Fig 3.4d). A post-hoc test found that people with glaucoma spent longer looking at obstacles per trial in all three conditions. Finally, people with glaucoma looked directly at the end-gates more often than healthy-eyed controls (group main effect: $F_{1,26} = 4.73$, $p = 0.039$).

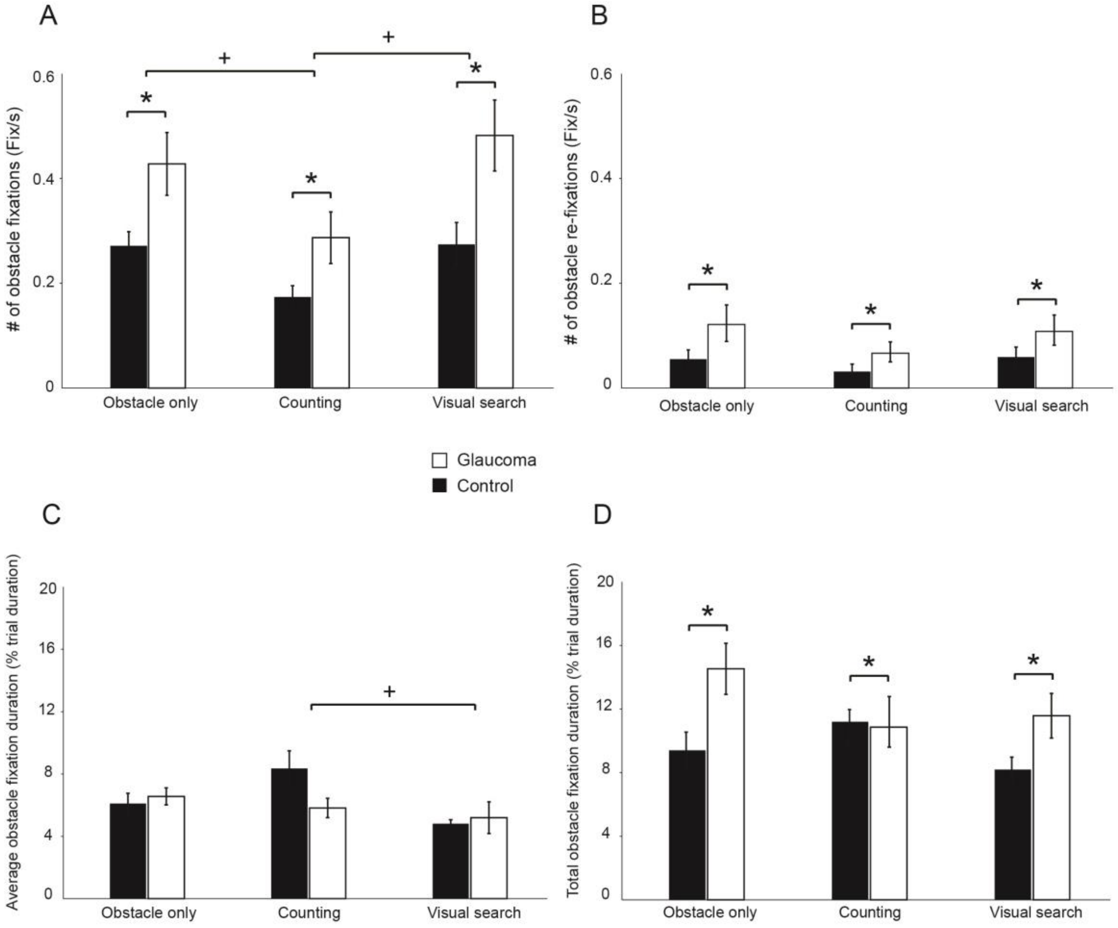


Figure 3.4: Mean (+/-SE) number of obstacle fixations (A), number of obstacle re-fixations (B), average obstacle fixation duration (C) and total obstacle fixation duration (D) are shown for both groups in all conditions. Group (*) and condition (+) main effects are shown.

Saccade - obstacle crossing timing, and gaze distance:

Analysis of the three measures that relate a person's position to the location of their gaze showed profound effects only for gaze distance. Neither of the saccade – crossing event timing measures showed differences (Fig 3.5). For the gaze distance measure, main effects of group ($F_{1,26} = 16.23$, $p = 0.0004$) and condition ($F_{2,52} = 3.32$, $p = 0.044$) were found (Fig 3.6). The nature of these differences were shown through post-hoc tests, such that the glaucoma group looked to areas in the environment that were closer to them in the AP direction compared to controls. Furthermore, gaze was directed further ahead during navigation in the obstacle only task, compared to the dual task conditions.

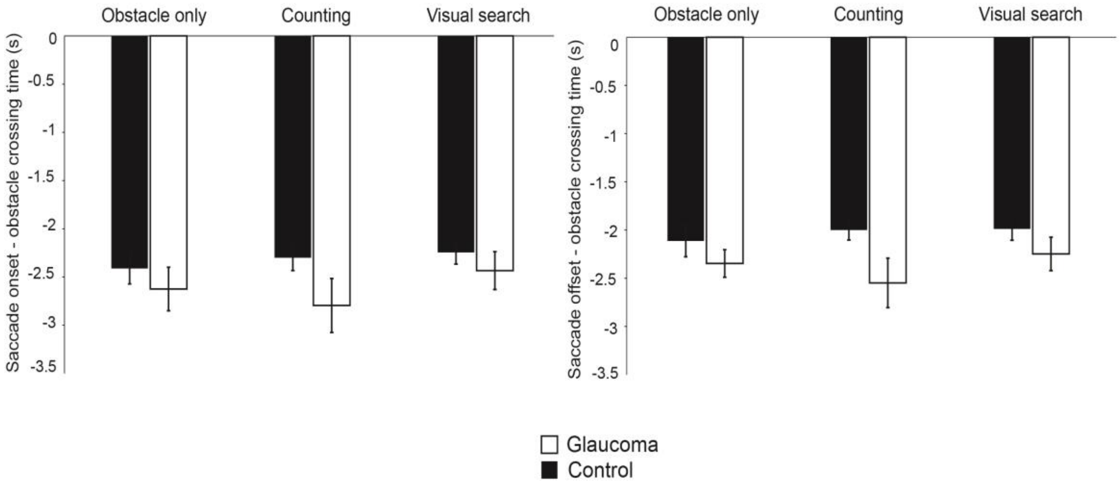


Figure 3.5: **Mean (+/-SE) saccade – obstacle crossing values are shown for both groups and conditions. A more negative value indicates subjects look to or away from an obstacle sooner with respect to when their chest crossed it.**

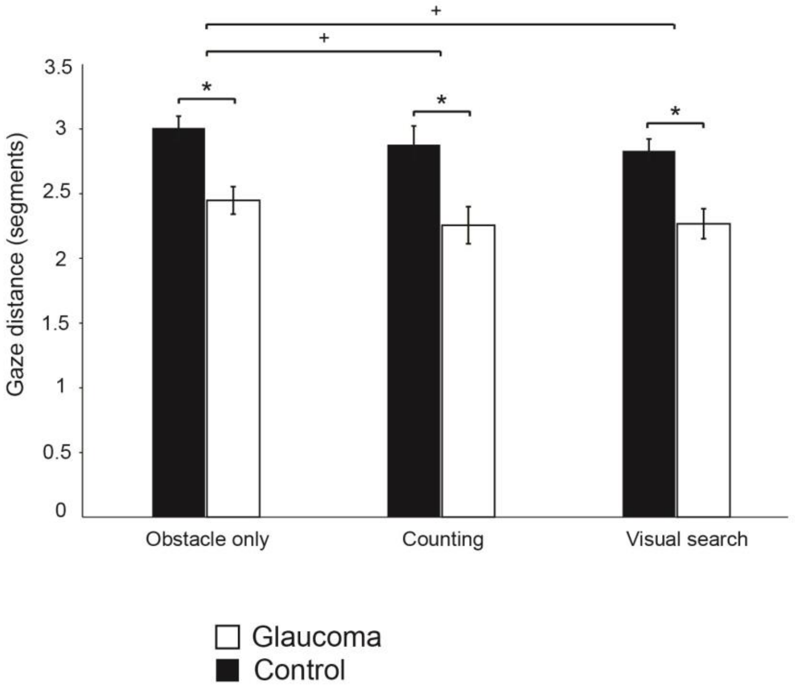


Figure 3.6: **Mean (+/-SE) gaze distance value averaged across a each trial (B) are shown for both groups in all conditions. Group (*) and condition (+) main effects are shown.**

3.3.2. Association with visual field loss:

Mobility:

Associations between mobility metrics and the severity of visual field loss were scarce during the obstacle navigation experiment. Two non-statistical trends were evident. Specifically, linear regression showed a weak relationship between obstacle collisions and visual field MD that failed to reach significance ($\beta = 0.261$, $p = 0.064$, $R^2 = 0.278$) during the visual search condition, and less so during the obstacle only condition ($\beta = 0.091$, $p = 0.097$, $R^2 = 0.231$), where more collisions tended to be made with worse visual fields.

Gaze Behaviour:

Several measures of gaze behaviour were associated with the severity of visual field loss for people with glaucoma. First, during the obstacle only condition, the average fixation duration on obstacles decreased with worsening best eye visual field MD ($\beta = -0.002$, $p = 0.032$, $R^2 = 0.355$) (Fig 3.7a). In contrast, the total time spent looking at obstacles increased as best eye visual field MD increased during the counting condition ($\beta = 0.004$, $p = 0.01$, $R^2 = 0.467$) (Fig 3.7b). Lastly, during the counting condition, the association between increasing number of obstacle re-fixations, and worsening visual fields approached, but did not reach significance ($\beta = 0.006$, $p = 0.06$, $R^2 = 0.285$). No comparisons of slopes relating gaze behaviour and visual fields were warranted, since no measures showed associations in multiple conditions.

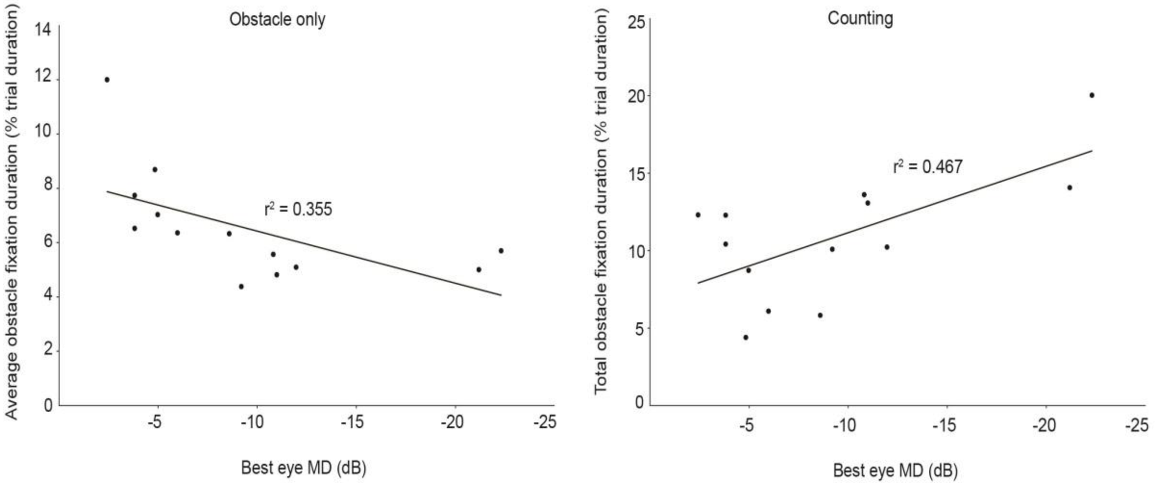


Figure 3.7: Results of regression analysis depicting relationships between average obstacle fixation duration over a trial (A) and total obstacle fixation duration over a trial (B) compared to visual field mean deviation (MD) for the glaucoma group are shown.

Saccade - obstacle crossing timing, and gaze distance:

No significant associations were found between the severity of visual field loss and the two saccade – obstacle crossing measures, or with gaze distance.

3.3.3. Association between mobility and gaze measures:

A limited number of mobility measurements showed evidence of a relationship to specific gaze metrics. During the counting condition, gait speed for the controls tended to increase with shorter (more positive) saccade from obstacle – crossing values (β = -0.254, p = 0.036, R^2 = 0.297). Subjects in the glaucoma group showed a strong trend toward increasing incidence of obstacle collisions when their average fixation duration on obstacles was longer during the counting task (β = 0.007, p = 0.061, R^2 = 0.284). Also, it should be noted that in the counting and search conditions, subjects with glaucoma who had a higher gaze distance measure, tended to look to the end-gates more often (β = 0.001, p = 0.0043, R^2 = 0.538; β = 0.002, p = 0.015, R^2 = 0.431). Of importance, subjects with glaucoma were found to have a higher number of collisions with obstacles if their gaze distance was less (β = -0.017, p = 0.04, R^2 = 0.33) (Fig 3.8). No comparisons of slopes were merited for associations between mobility and gaze measures, since multiple correlations across conditions between the same two parameters were not found.

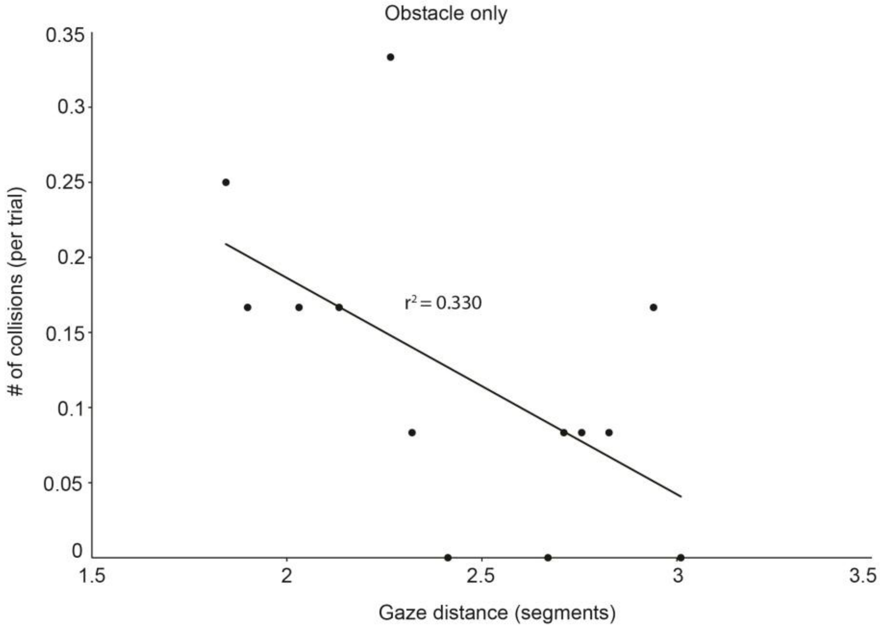


Figure 3.8: Regression analysis showing number of obstacle collisions per trial compared to gaze distance in segments. Analysis revealed a significant relationship between the two, where the number of collisions decreases with further average gaze distance.

3.3.4. Dual task cost:

Dual task performance:

Costs to counting secondary task performance were found in both controls (T = -4.87, p = 0.0002) and subjects with glaucoma (T = -10.50, p < 0.0001). Also, costs in the counting task were greater for the glaucoma group compared to controls (T = -5.11, p < 0.0001). This means that subjects with glaucoma had greater decreases in the counting secondary task performance while walking. Visual search performance did not drop for either group during walking compared to baseline.

Visual search task gaze behaviour to shapes:

One-way ANOVAs comparing shape fixation parameters between groups during the visual search conditions did not show any main effects.

3.4. Discussion:

Vision supplies us with the information we need to navigate through complex environments. Both central and peripheral vision contributes to path navigation during walking by assessing self-motion, identifying environmental features, and updating our representation of our overall surroundings (Turano et al., 2005). The aim of this study was to investigate how people with reduced peripheral vision due to glaucoma navigate through a series of obstacles, and the gaze behaviours used to accomplish this feat. Our findings indicate that people with glaucoma collide with obstacles in their path more often, walk more slowly, and alter their trajectory more than healthy older adults. Also, participants with glaucoma look to obstacles in their path more frequently and spend a greater portion of their time looking at them during navigation. Importantly, people with glaucoma also look to features of the environment (the ground or obstacles) that are closer to them in relation to their goal. Multitasking, either from counting or performing a visual search task, exacerbated these effects.

3.4.1. Effects of glaucoma on mobility during obstacle navigation

This study sheds light on the mobility limitations people with glaucoma experience when walking and navigating around obstacles. We found that people with glaucoma are more likely to have collisions with obstacles when dual tasking, compared to controls, and compared to when no dual task was performed. Also, they walked slower in all conditions compared to controls. Both results are comparable to those of Freidman and colleagues (2007), who found higher incidence of collisions and slower gait in a much larger cohort of participants, on a longer obstacle course. Given the trends in our data, it is expected that with more participants, there may be statistical power to detect a difference in number of collisions when walking without dual tasking as well. The substantial increase in collisions that occur in people with glaucoma during dual tasking was not seen in control subjects. This finding stresses the importance that dual tasking has on mobility and collisions during walking, which may lead to harmful falls in people with glaucoma. During obstacle navigation, strong trends were identified showing that the severity of visual field loss in the participants with glaucoma was related to a higher incidence of collisions, suggesting that mobility becomes worse when vision is lost. Currently, only binocular over monocular visual field loss has been shown to increase the number of collisions, but not the level of visual field loss (Friedman et al., 2007).

While path choice was not affected by the presence of glaucoma, people with this disease had greater trunk trajectory variability. This suggests that when trying to avoid poles, restricted visual fields cause participants to direct their torso more toward gaps between obstacles to find a safe path (i.e., divert from a straight line trajectory), but this does not prevent collisions. In addition, the presence of a cognitive dual task (i.e., counting) causes even greater trajectory variation. Gait speed is often used as a gross indicator of mobility function (Freidman et al., 2007; Peel et al., 2012) and the slower walking speed seen with glaucoma, which is worse during dual tasking, speaks ill of this population's walking ability in natural environments.

3.4.2. Effects of glaucoma on gaze behaviour during obstacle navigation

Visual sampling of our environment allows us to navigate around obstacles and select a safe path. The pattern of fixations to task-relevant areas was altered for people with glaucoma in this study. During obstacle navigation, fixations are not always made to hazards, and are often directed to future goals and footfall locations (Franchak & Adolph, 2010). Indeed, when navigating a crowded area to an end goal, findings in the literature suggest that features that make up the path borders and the end goal location are the primary focus of fixations (Patla et al., 2007). We showed evidence for obstacles and end goals being fixated intermittently during navigation, with a higher proportion found for participants with reduced peripheral vision. Specifically, participants with glaucoma fixated on obstacles more often, re-fixated the same obstacle more often, and spent a higher proportion of the total time fixating obstacles. With greater glaucoma severity, participants were more likely to have shorter fixations to obstacles, but spend more total time looking at them. The culmination of this gaze behaviour may negatively impact one's ability to obtain a sufficient visual representation of the environment for guiding walking, as trends in our data show higher rates of obstacle collisions with worse visual fields. In comparison, Galna and colleagues (2012) found that people with Parkinson's disease made more saccades prior to turning around an object than controls, but during a cognitive dual task, they made less frequent saccades when preparing for a turn. This suggests that gaze behaviours during walking are highly dependent on the visual and mobility capacities of different patient populations.

The function of gaze fixations during obstacle navigation is to allow the identification of safe corridors while minimizing path deviations from the end-goal (Patla et al., 2007). Our data suggests that people with glaucoma are more concerned with identifying hazards and the end goal location, but do not direct their gaze as far ahead in their travel path. Instead, for all conditions it was found that people with glaucoma fixated closer to their feet as they walked. The lower peripheral visual field is crucial for guiding foot placement and monitoring limb trajectory and hazards as we walk in complex environments (Marigold, 2008). Our results indicate that with reduced visual fields, participants are more concerned with the areas (floor and obstacles) closer to them, since they cannot be as effectively monitored using peripheral vision. This is despite the fact that they have a tendency to look ahead more frequently to the path end location and for a greater amount of time. However, this cautious gaze strategy does not protect against collisions with obstacles. In fact, participants who looked closer to their feet were more likely to collide with poles.

Our findings support research showing that, in other tasks like picture viewing, people with glaucoma look to areas of the scene more frequently (Smith et al., 2012). However, in a virtual driving scenario, people with glaucoma failed to recognize dangerous hazards in the environment despite an increased rate of saccades (Crabb et al., 2010). Similarly, in our experiment, more fixations were made to hazards and task goals, and while this did not lead to problems with path choice, it did not prevent against problematic collisions with hazards. In simpler walking environments, evidence for differing gaze behaviour due to visual field loss is conflicting. For example, when walking across an empty intersection, no differences in gaze behaviour were seen (Geruschat et al., 2006). In contrast, when walking down an empty hall to a door, people with visual field loss looked to more areas that were not task-relevant (Turano et al., 2001). Our findings are an important addition to this body of research, and suggest that in more complex walking tasks, which may put an older person at a higher risk for falls, there are differences in gaze behaviour that do not protect against mobility concerns.

It should also be noted that while both dual tasks led to worse mobility performance and altered gaze behaviours, the counting secondary task was the only one where evidence of performance declines were found. This may be due to the differing nature and/or difficulty of each task, but both cognitively demanding and visually distracting dual tasks are important for investigation, as they each impact gaze and mobility to different, but significant, degrees.

3.4.3. Conclusion

This research investigated the nature of mobility problems experienced by people with glaucoma during obstacle navigation, and for the first time, the gaze behaviours that relate to them. Our findings indicate that older adults with glaucoma have a lower ability to avoid collisions with obstacles, to maintain a normal speed, and to minimize changes in chest trajectory while navigating through stationary obstacles. In addition, gaze behaviour varied such that obstacles and path end location was fixated more frequently and for longer duration, while gaze was also directed closer to the feet compared to controls. Mobility measures and gaze measures varied during dual tasking for those with glaucoma such that more collisions were made, and obstacles were fixated for more or less time, depending on the nature of the dual task. Future research should investigate those gaze behaviours that are protective of mobility and limit falls during obstacle navigation, also while dual tasking. Furthermore, similar investigation of gaze and mobility characteristics in people with impairment affecting other areas of their vision should be conducted.

Chapter 4. General Discussion

This thesis examined the effects of glaucoma on both mobility and gaze behaviour during two common visually guided walking tasks under single- and dual-task conditions. Older adults with glaucoma were less accurate with foot placement and had difficulty avoiding collisions with obstacles in their path. Also, the data indicated that gaze behaviour was modified such that during precision walking, important timing relationships between stepping and looking to targets was disrupted. Also, during obstacle navigation, subjects with glaucoma did not look as far ahead and fixate hazards more often compared to controls. Many of these effects were worse for those with glaucoma as visual field loss increased, and several mobility measures also correlated with gaze metrics. In addition, dual tasking negatively impacted mobility and altered gaze behaviour on both walking tasks, but the characteristics of the changes were dependent on the nature of the dual task. Taken together, reduced peripheral vision resulting from glaucoma alters gaze behaviour and negatively affects foot placement and body trajectory control in ways that are related to falls risk. A small number of studies have shown people with glaucoma have difficulty navigating obstacles (Friedman et al., 2007), and have altered gaze behaviours associated with reduced visual fields (Turano et al., 2001), but none have investigated the relationship between mobility measures and gaze behaviours in complex walking tasks.

4.1. Relationship between studies

The two studies of this thesis investigated the effects of glaucoma on mobility and gaze behaviour with and without dual tasking during different walking tasks. Study one (Chapter 2) revealed greater foot placement error and variability, and similarly, study 2 (Chapter 3) showed glaucoma leads to more collisions with obstacles. Gait speed is often reported as a strong indicator of mobility function in older adults (Peel et al., 2013). Although gait speed did not differ between groups for the target stepping task, the glaucoma group walked much slower during obstacle navigation. This relationship persisted for all dual task conditions in the obstacle navigation task. The different effects between tasks may be related to the fact that the obstacle task is, or at least is perceived as, more challenging for the people with glaucoma.

The effects of glaucoma on gaze behaviour were evident in both studies, but sometimes manifested in different ways with respect to fixations to areas of interest. While the precision walking experiment required subjects to identify footfall locations along a path, the obstacle navigation task required subjects to identify an optimal path choice and the location of vertical obstacles to walk around. When comparing the fixation behaviour of the glaucoma to the control group, there was no differences in the number of times stepping targets were fixated, but found that the glaucoma group fixated obstacles much more frequently. Despite the differing nature of the tasks, which dictated the specific visual information required for successful performance of each task, areas of interest that were integral to the task (targets/obstacles) were re-fixed more often by the glaucoma group. Together, these results align with that of studies involving other tasks, which suggest people with reduced visual field fixate the same areas more frequently, but that this does not prevent them from missing important regions in their environment (Crabb et al., 2010).

The relationship between movement timing and gaze shifts towards AOIs was a major focus of both studies. While study one showed a disrupted timing relationship between saccades to/from targets and stepping events toward them such that foot placement was not monitored as effectively in people with glaucoma, study two showed that they looked to areas closer to themselves with respect to the end of the path. Again, the important distinction between gaze behaviours in various walking tasks is evident. During precision walking, looking further ahead is related to poorer stepping, and during obstacle navigation, looking closer to the feet is related to more obstacle collisions. Therefore, one uniform change in gaze behaviour does not exist across both tasks.

The dual tasks altered gaze behaviour in both walking tasks, but each secondary task had its own unique effect. These effects were similar across both walking tasks, as the cognitive dual task condition led to a lower number of fixations to AOIs in each. This is evidence of participants exceeding their attention capacity to the point where the normal amount of focus on AOIs is reduced. Similarly, the main effect of the visual search dual task, which by its very nature distracted vision from AOIs related to walking, caused shorter average fixation duration on those AOIs. This secondary task affected gaze behaviour to a greater degree during precision walking, as the number of re-fixations to walking AOIs, and the total fixation duration to each, were reduced. The more drastic effects of dual tasking on gaze behaviour for the glaucoma group on both tasks may be related to their reduced divided visual attention ability when compared to controls, as revealed by the UFOV test number 2. Together, these two studies show that under different walking circumstances, the pattern of effects of each dual task remained true, and also that both altered mobility to a significant degree. Performance on the cognitive secondary task collectively revealed that for both walking tasks, controls and glaucoma subjects had reduced counting performance, and that in both cases, the glaucoma group had greater costs. In contrast, the visual search secondary task performance decreased during dual tasking for both groups during precision walking, but not during obstacle navigation. An unexpected finding was that costs were not more evident for the visual search task in the glaucoma group compared to control for either walking task. However, it is important to note that gaze behaviour was disrupted by the visual search task, and both dual tasks negatively impacted mobility to a similar degree overall.

In summary, glaucoma led to mobility deficits in two distinct visually guided walking tasks, and disrupted gaze behaviour in each. The nature of the disruption had similarities regarding fixations to AOIs, but had different effects on measures that related mobility timing to gaze. In addition, performing the two dual tasks negatively affected mobility performance in both walking tasks, and their impact on gaze behaviour depended on the nature of the dual task.

4.2. Study Limitations

Several limitations regarding technical constraints that affected experimental design, and those with respect to the participants were present in this study and are described here. The first limitation to the study was that although all subjects performed the two walking tasks, they could not be counterbalanced due to technical constraints. Different methods of obtaining gaze data were used in order to optimize the quality of the data for each study. Study one (Chapter 2) required that we see the location of gaze on the ground, often very close to participant’s feet. Thus, we used the Eye-head integration feature of the ASL equipment to obtain an image of the environment from a stationary scene camera mounted behind and to the left of the subject. Set-up for this method can take 30-45 minutes, and because the testing session was already approximately 3 hours, we opted against doing the precision walking task second, so that it could be set up prior to the subject's arrival. In contrast, for the obstacle navigation study, a simpler set-up was used, where gaze locations were obtained with respect to the head-mounted scene camera. This set-up could be done in 5 minutes between studies. This limitation may have impacted the effects of the dual tasks. For example, every subject had already been tested on their dual tasking ability during the precision walking task, before they performed the obstacle navigation task. This may have contributed to the lack of dual task costs on the visual search secondary task during obstacle navigation. However, very strong effects on counting performance were still seen during obstacle navigation, and therefore, the lack of visual search performance decline was more likely due to the nature of the obstacle navigation task, than the order of tasks.

A second possible limitation was the way baseline measurements for dual task performance were obtained. For the counting task, baseline and dual task performance were normalized to correct counts/second, and were therefore easily compared. However, baseline counting performance was recorded while seated, which may have led to differences compared to when walking. It is possible that baseline counting performance could have been taken during walking without targets or standing, but in the postural control literature standing while performing a cognitive task is considered dual tasking (Huxhold, et al., 2006). Therefore we decided to take baseline counting performance while the subject was seated in order to obtain a comparison between absolute baseline performance and performance during precision walking. Also, the baseline for the visual search condition was taken over four seconds. This duration was chosen because this was a typical time pilot subjects could see the shapes while walking. Ideally this duration would be exactly the same as each walking trial, however this duration was somewhat variable, and not known until the subject actually did the walking experiments. Therefore, a four second duration was the best approximation. Similar to the counting baseline, visual search baseline could also have been taken during walking without targets or obstacles; however, we used the same rationale as the counting task based on the fact that standing introduces a type of dual task.

A third limitation was the sample size of each group. Recruitment was done through a local ophthalmologist, and we were therefore dependent on that office for finding glaucoma participants. In some cases only a few more subjects would likely have pushed strong statistical trends to a significant level. Also, the distribution of visual field loss in the best eye across glaucoma subjects was not uniform from zero to -25 dB. As described above, visual field loss leads to poorer quality of life, more problems with mobility, and more concern with falling (Nelson et al., 1999; Popescu et al., 2012; Tanabe et al., 2012). This makes it more difficult to recruit subjects with severe vision loss, who are more wary of leaving their homes and going to a new place. Our results do show strong associations across visual fields for many measures, so in most cases the visual fields of our glaucoma participant pool was sufficiently dispersed. More importantly, strong group differences were noted in both tasks in several measures.

Lastly, our experiments were conducted in a laboratory setting with many aspects controlled, and therefore, may affect the generalizability to real-world walking. Nonetheless, the walking tasks, including the dual-task aspects, were designed to simulate real-world walking situations, such as stepping around puddles or cobblestones, or navigating through a crowd while having a conversation with someone. Our results should therefore be applicable to walking in natural environments. Also, precision walking and obstacle avoidance are commonly used to assess mobility function during visually guided walking tasks in young and older adults (Chapman & Hollands, 2006; Friedman et al., 2007).

4.3. Implications and recommendations

This research effectively and convincingly shows for the first time that mobility and gaze are affected during visually guided walking tasks for people with glaucoma, and that the two are associated with one another. These findings provide the foundational research needed to identify stepping and gaze training characteristics that spare mobility in people with glaucoma and prevents collisions and falls. Importantly, during precision walking the timing relationship between looking to targets and stepping to them is associated with mobility defects (Chapman & Hollands, 2006; 2007), and worsens as vision is reduced. This highlights the need for interventions early on in the progression of glaucoma to attenuate this behaviour as vision worsens, and to aid in the preservation of proper walking ability. Such training has found success in older populations who were at high risk for falling (Young and Hollands, 2010).

Currently, gaze training with the intent to improve mobility in people with low vision is limited to computer systems that aim to improve search speed and accuracy (Kuyk et al., 2010). These methods have proven unsuccessful for improving mobility, and future gaze training should involve gaze and mobility instruction and practice on real complex walking tasks. An optometrist or ophthalmologist implements low vision rehabilitation in the United States, but treatment models are not uniform (McAllister & Kammer, 2014). Unfortunately for those with glaucoma, rehabilitation techniques related to visual field loss are primarily geared toward improving quality of life for those with central visual field loss (McAllister & Kammer, 2014). Similarly, optical visual enhancement systems such as magnifiers and telescopes are mainly geared toward improving vision for people with central vision loss (McAllister & Kammer, 2014). Augmented-vision devices using head mounted displays for people with peripheral vision loss are being tested, with some success at reducing visual search speed, but not for collision judgment (Luo & Peli, 2006; Luo et al., 2009). These types of devices do show promise for the future, and may benefit from technological advancements to make them more effective and ergonomic (Hwang & Peli, 2014). Trifield lenses used to enhance visual field range have also been tested for people with peripheral vision loss, but have had mixed results in crowded environments (Woods, et al., 2010). An alternative approach that could be used in conjunction with gaze training based on our research is portable collision warning devices that have shown success for people with peripheral vision loss and the blind in an obstacle course (Pundlik, et al., 2015).

The results of these studies also point to the significant role multitasking has on mobility and gaze behaviour for people with glaucoma. Thus, future gaze/mobility training should incorporate these aspects in order to apply to everyday life.

Another finding with implications for future research is the fact that a dose-response relationship between both mobility/gaze behaviour and visual field loss exists. Future studies must consider the severity and location of a person's visual field loss, and any training protocols must acknowledge that people with worse visual fields are at a greater disadvantage. Therefore, training options may need to vary depending on the severity of vision loss. Also, it is unknown if training someone with glaucoma to revert to normal gaze behaviours will be beneficial. In fact, the changes in gaze behaviour may be protective against mobility problems that would be even worse if normal gaze behaviour persisted.

It is our recommendation that gaze/mobility training be implemented to restore normal saccade timing relationships during precision walking tasks (spend longer looking at the impending footfall target). It is less clear if people with glaucoma should direct their gaze further ahead when navigating through crowded areas. Also, older adults with glaucoma should be made aware of the impact different dual tasks can have on mobility. Instead of attempting to do multiple things at once, it is recommended that people with glaucoma focus most of their effort on walking, and stop walking to identify important feature of their surroundings or to execute a complex mental task.

In summary, these findings inform future research for improving mobility and reducing falls in people with glaucoma. This will ultimately lead to better quality of life for this growing population.

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